Modeling, Simulation, and Energy Performance of VFD and On/Off HVAC Systems

BY

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Dedicated to my parents, my wife, my brothers, my siblings and my teachers

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All the praise is for Allah, the one and the only God, the Lord of the worlds. Peace and blessings be upon the greatest human being that ever walked this earth, the last and the final Prophet, Muhammad (peace be upon him), and upon his children, wives and companions. I start by thanking Allah for all He has provided me and this time it's a master's degree, which I had always desired pursuing.

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LIST OF ABBREVIATIONS

HVAC	:	Heating, Ventilation and Air Conditioning
VFD	:	Variable Frequency Drive
VSD	:	Variable Speed Drive
A/C	:	Air Conditioning
MATLAB	:	Matrix Laboratory
rpm	:	Revolutions per minute
hp	:	Horsepower
BTU	:	British Thermal Unit
LabVIEW	:	Laboratory Virtual Instrument Engineering Workbench
DAQ	:	Data Acquisition
PC	:	Personal Computer
cDAQ	:	Compact Data Acquisition
NI	:	National Instrument
MAX	:	Measurement & Automation Explorer
THD	:	Total Harmonic Distortion
RMS	:	Root Mean Square

SCRs	:	Silicon-Controlled-Rectifiers
IGBTs	:	Insulated-Gate-Bipolar-Transistors
c.pCO	:	Connected Programmable Controller
ExV	:	Electronic Expansion Valve
comp	:	Air Conditioning Compressor
CC	:	Compressor Contactor
FM	:	Air Conditioning Fan Motor
BM	:	Air Conditioning Blower Motor
BMC	:	Blower Motor Contactors
ECB	:	Electronic Control Board
BLDC	:	Brushless DC Compressor
CB	:	Circuit Breaker
pGD[1]	:	Programmable Graphic Displays
FBUS RTU	:	Frame Transport Bus for Remote Terminal Unit
IPM	:	Intelligent Power Modules
BMS	:	Building Management Systems
PID	:	Proportional, Integral and Derivative

LIST NOF NUMERICALS

$\dot{M}_{HVAC}$: Mass supply air flow (kg/s)

M_{air} : Air mass (kg)

C_p : Air specific heat (J/kg.k)

R_{eq} : Equivalent house thermal resistance (R_{in}+R_{out}).

Q_{int} : The sum of convective internal load ($Q_{int} = Q_{Heat\ sources}$)

$T_{outdoor}$: Out-room temperature (^{o}C)

T_{room} : In-room temperature. (^{o}C)

T_{HVAC} : Supply temperature (^{o}C)

T_{House} : The inside house temperature. (^{o}C)

T_{mass} : The inner mass temperature. (^{o}C)

T_{out} : The outside house temperature. (^{o}C)

C_a : The thermal mass of the air.

C_m : The thermal mass of the building and furniture.

U_a : The conductive of the building envelope ($U_a = 1/R_{out}$).

U_m : The conductance between the inner air and inner solid mass ($U_m = 1/R_{in}$).

Q_a	:	The heat flux consists of three gain factors (J/s)
Q_{in}	:	Internal heat gain (J/s)
Q_{so}	:	Solar heat gain (J/s)
Q_c	:	Heating/Cooling gain (J/s)
Q_m	:	Mass supply air flow rate (J/s)
A	:	Area (m^2)
H	:	Heat transfer coefficient
k	:	Thermal conductivity
h	:	Radiation coefficient
l	:	Thickness (m)
$T_{\_out}$	:	External house temperature (℃)
$T_{\_H}$	:	Internal house temperature (℃)
$T_{\_1}$	:	Internal roof temperature (℃)
$T_{\_2}$	:	Internal wall temperature (℃)
$T_{\_3}$	:	Internal windows temperature (℃)
$C_{\_Air}$	:	Specific heat of air (J/℃)
$M_{\_Air}$	:	Mass of air inside the house (kg)

$c_{\_Air}$: Heat capacity of air

$C_{\_Roof}$: : Specific heat of roof (J/℃)

$M_{\_Air}$: Mass of roof (kg)

$c_{\_Roof}$: Heat capacity of roof

$C_{\_Wall}$: Specific heat of wall (J/℃)

$M_{\_Wall}$: Mass of wall (kg)

$c_{\_wall}$: Heat capacity of wall

$C_{\_Wind}$: Specific heat of windows (J/℃)

$M_{\_Wind}$: Mass of windows (kg)

$c_{\_wind.}$: Heat capacity of windows

$Q_{\_Air}$: The energy stored in the space area of house. (J/s)

$Q_{\_Wall}$: The heat energy stored in the wall. (J/s)

$Q_{\_Roof}$: The heat energy stored in the roof. (J/s)

$Q_{\_Wind}$: The heat energy store in the windows. (J/s)

$Q_{\_(Heat\ house\ Sources)}$: The heat energy supplied from activity human and furniture in the space area of house. (J/s)

$\frac{dQ_{Cooler}(t)}{dt}$: The absorbed heat flow form air house by cooler.

K_0	:	The effective cooler gain kg/K (default $K_0 = 1\ \mathrm{kg/K}$).
K_1	:	The effective time cooler gain kg/s.K (default $K_1 = 1\ \mathrm{kg/s.K}$).
K_2	:	The effective HVAC gain (default $K_2 = 0.005$).
K_3	:	The effective time HVAC gain s^{-1} (default $K_3 = 0.9\ s^{-1}$)

ABSTRACT

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Saudi Arabia (SA) is characterized by high climate states such as temperature, humidity, warm wind, and dust storm. Air-Conditioning systems play a prominent role and hence constitute the majority of power consumption of the kingdom. In order to achieve efficient energy consumption for a constantly varying air conditioning load it is very necessary to asses and evaluate the thermal model of a building.

The thesis investigated the thermal house model and its interaction with both ON/OFF and VFD technologies for home air conditioning. The second order heat model is introduced in this work for residential load in Dhahran area using MATLAB/SIMULINK tools. The newly developed model is simulated using Simscape Physical Components. The simulated model is subjected to ON/OFF cooling source and controlled cooling source (VFD source). The two technologies were installed at two similar campus residence for energy performance and subsequently used for the developed model validation. LabVIEW based data acquisition system was installed along with the complete electrical and thermal setup. The model validation results have shown very good compatibility with the experimental results. Energy performance comparative study has indicated about 20% to 50% gain in energy in favour of VFD technology

ملخص الرسالة

الاســـــم الكامــــل: [وليد محمد عبده حمنة**]**

عنـوان الرسالــــــة: [نمذجة و محاكاة لأداء الطاقة في نظام التدفئة والتبريد بإستخدام تقنية التردد المتغير(VFD) والتبريد بتقنية الفتح والغلق (ON/OFF) **]**

التخصـــــــــــــــص: [الهندسة الكهربائية**]**

تاريخ الدرجة العلمية: [مايو- 2016**]**

تتميز المملكة العربية السعودية (SA) بطبيعة الدول الاستوائية مثل إرتفاع درجة الحرارة والرطوبة والرياح الدافئة والعواصف الترابية. ولذالك أنظمة تكييف الهواء تلعب دورا بارزا، حيث تشكل الغالبية العظمى من استهلاك الطاقة في المملكة. من أجل تحقيق ترشيد استهلاك الطاقة لأحمال مختلفة من تكييف الهواء فمن الضروري جدا تقييم وتقدير النموذج الحراري للمبنى.

إطروحة هذه الرسالة تعرض وتناقش تصميم وتحليل وتقييم نموذج منزل الحراري وربطه مع نوذج للنظام التدفئة والتبريد للمنازل بإستخدام التقنية ON/OFF وتقنية VFD (والتي تعني التحكم بالطاقة المستهلكة عن طريق تغير تردد تيار الظاغط). النموذج الحراري من الدرجة الثانية المحسنة لبيت سكني في منطقة الظهران ،المملكة العربية السعودية ، يكون يبنى بإستخدام برنامج الماتلاب SIMULINK/MATLAB. حيث يتم محاكاة النموذج الحراري المطور للمنزل بإستخدام المكونات المادية (Simscape Physical Components). يخضع النموذج الحراري لمحاكاة المنزل لمصدر تبريد متناوب (ON/OFF) ومصدر تبريد متغير (VFD) كلاً على حدى. تم إنشاء وحدتي تكيف بإستخدام التقنية ON/OFF وتقنية VFD في اثنين من المنازل المتماثلة في الحرم الجامعي لأداء الطاقة واستخدامها في وقت لاحق للتحقق من صحة نموذج متطور. نظام مراقبة وحفظ للبيانات الكهربائية والبيئية يبنى بإستخدام برنامج LabVIEW (والذي يعني اختصارا بطاولة العمل لمختبر الأجهزة الهندسية الافتراضية) في كلا المنزلين. وقد تبين أن نظام التكيف بالتردد المتغير(VFD) يمتلك مزايا في حفظ الطاقة مقارنة بنظام التكيف التقليدي المتناوب (ON/OFF). فالنتائج التي تم الحصول عليها ببرنامج LabVIEW تظهر مصداقيتها بالمقارنة مع نتائج التحليل المعتمدة على المحاكاة SIMULINK/MATLAB حيث تظهر درجة جيدة من الدقة. حيث أن كمية الطاقة المحفوظة تتراوح مابين 20% الى 50% معتمده على الظروف البيئية المحيطة مثل درجة حرارة المحيط والنشاطات الحرارية داخل المنزل و درجة الحرارة المطلوبة بداخل المنزل.

CHAPTER 1

INTRODUCTION

“Around 70 percent of electricity consumption in Saudi Arabia go on air conditioning and with more than 1.5 million new homes needed to keep pace with population growth, domestic energy demand is anticipated to double by 2030,” said Dr. Saleh Al Awaji, Deputy Minister of Water and Electricity, ahead of the first Saudi Heating, Ventilation and Air Conditioning (HVAC) conference on Feb. 11-13, Riyadh [1]. Therefore, the prerequisite in the electrical energy sector in Kingdom of Sadia Arabia (KSA) for sustainable cooling system solutions should be enhancement energy efficiency. Accordingly, sustainable techniques and technologies, which require generating electricity will diminish consuming energy, also decrease the amount of innovative materials. With growth dramatically population in KSA, the kingdom’s electricity company blueprints to devote $80 billion to possess demand which may be reach to more than $30*10^3$ megawatt’s by the next decade [1]. Using inefficient devices leads to big energy consumption, with the hot weather in the kingdom that occurs almost during eight months a year. Around (55 to 65)% of energy generation is consumed by cooling loads [2]. Therefore, the traditional ON/OFF HVAC technology is no more an optimal for cooling.

Variable frequency/speed technology of the compressor and blower in central air conditioning system will allow the compressor speed to match the cooling capacity of the cooling load of the residence. The resultant of using variable frequency drive (VFD) in the air conditioning system will increase the efficiency working compared to a traditional system with ON/OFF cycle capacity control, which reflect on electric energy saving.

1.1 Air Conditioning

Air-conditioning (A/C) is exactly what the name suggests; air has been conditioned to meet the demand of the occupants of a home, office, factory or any internal spaces. Air-conditioning delivers and maintains internal air conditions at a desired set temperature, regardless of the day and time of year, the season or the country of residence.

1.2 ON/OFF Cycle A/C System

The air conditioner attains the desired temperature based on the temperature set on by its thermostat. When the compressor in the air conditioner is turned ON, it will remain on until the room temperature decreases to desired temperature on the thermostat. Once the desired temperature is reached, the compressor turns off until the room temperature increases again. Figure 1.1 shows a cycle of the air conditioner that explains ON/OFF time, of the compressor and blower. The cycle time of an air conditioner is the amount of time the unit runs to maintain the temperature of the rooms equals to the set point temperature. If set point is set a very low temperature as compared to the room temperature, the compressor will work for a longer to meet the set point, thus, increasing the cycle time. In other words, bigger difference between the room temperature and thermostat temperature, bigger cycle time will be done and vice versa.

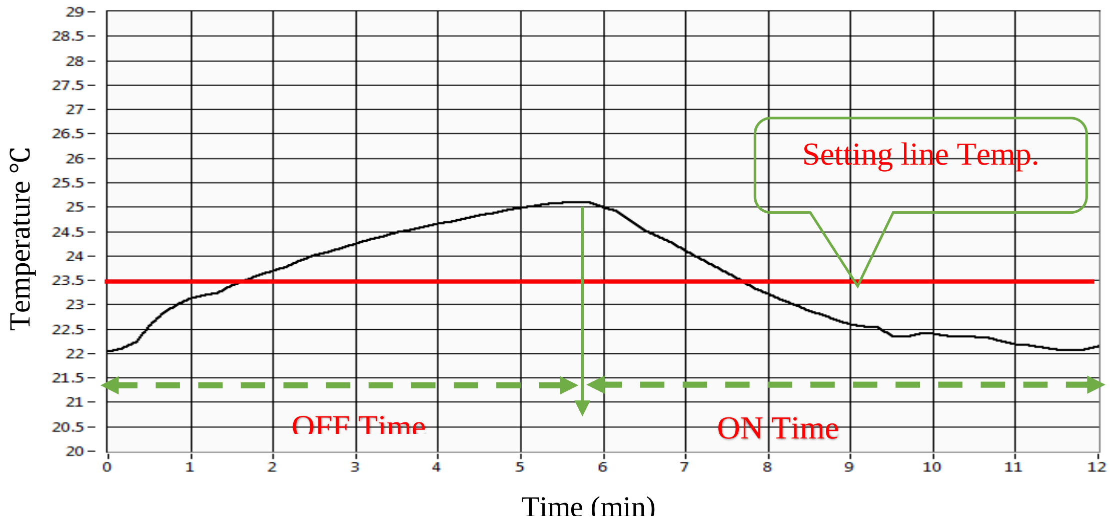


Figure 1.1 Typical ON/OFF Cycle for A/C System

1.3 Variable Frequency Drive and A/C Systems

A Variable Frequency Drive is like the speed regulator on a car. It adjusts the speed of an HVAC fan or compressor motor, based on demand, to save energy and to extend motor and mechanical components life. Without a VFD, an HVAC fan or pump motor is either fully ON or fully OFF. Figure 1.2 shows a normal performance of VFD HVAC where the in-house temperature does not have periodic time (ON/OFF time) and it is always ON. In-door line temperature is closely to setting line temperature. A VFD eliminates the initial power surge and mechanical shock of switching the motor from OFF to ON. A VFD changes the speed of an HVAC fan or motor pump by adjusting the frequency. Typical frequency adjustment range in HVAC applications is from 10 - 60Hz. A VFD is wired in series between main power supply and motor for compressor/blower. Induction motors that typically used for compressors and fans in air conditioning systems are sized to handle maximum load under worst-case conditions and then leaving them to run at full power. They are fixed-speed motors. Their speed is determined by the constant frequency of the power supply (typically 50 or 60 Hz).

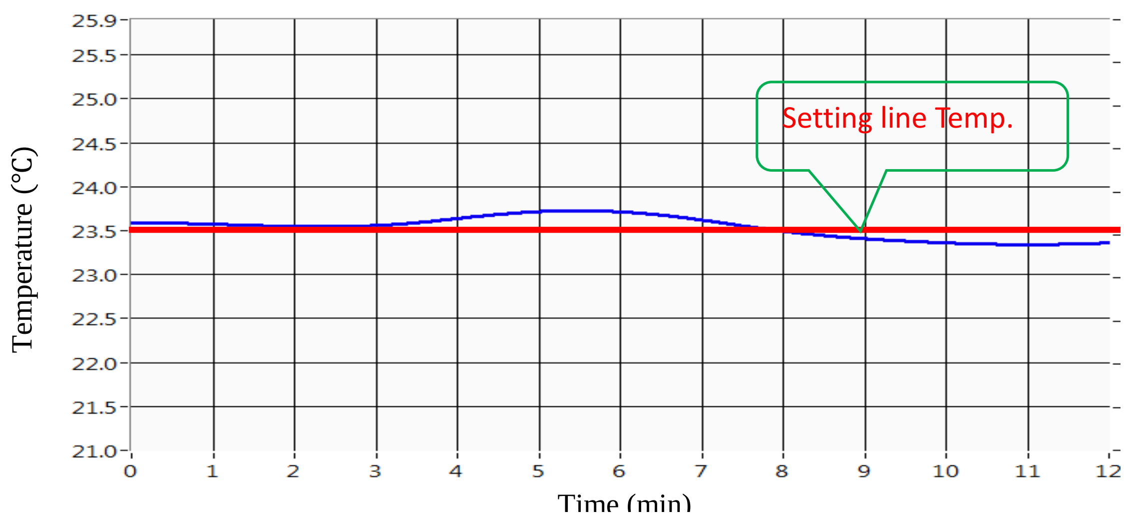


Figure 1.2 Typical Performance VFD Air Conditioning System

VFD or frequency inverters are solid-state devices and save energy whenever electric motors run at less than full speed. VFD is actually a frequency converter in which 50Hz or 60Hz AC input voltage is rectified into DC then is converted back into variable-frequency ac voltage. It must be noted that the power demand of motor varies with the cube of the motor speed, i.e. power is proportional to $f(speed)^3$ [3]. This means that a reduction of speed by 20% will result in reduction of power consumption by nearly a half, i.e. 50% saving. Since most HVAC equipment seldom runs at full power, significant energy savings can be made with these variable speed drives. Frequently, VFD is specified to save money by reducing energy consumption in pumps, fans, compressors, or any other motor loads that may be found in a typical building. These best practices will provide the engineer with information on how to specify a VFD to meet load conditions while achieving efficiency. In building systems, excluding constant horsepower and constant speed/torque loads, typical loads that can take advantage of VFDs divided into two primary categories:

1. Variable speed, variable torque (fans, blowers, and centrifugal pumps)
2. Variable speed, constant torque (positive displacement loads such as screw compressors, reciprocating compressors, or elevators).

Therefore, to support a characteristic load, we select a motor to meet a specific starting requirement and running output power, torque, and speed. However, through the affinity laws, we recognize that there are significant potential energy savings associated with reducing a motor’s speed and, by association, horsepower. So if we can define the required change in motor speed to meet the change in flow for a centrifugal load, the change in required power is proportional to the cube of the change in speed from one system point to another [3]. The change in required torque is proportional to the square of the change in speed from one system point to another. These relationships will be express through the following equations:

$$\frac{hp_1}{hp_2} = \frac{(rpm_1)^3}{(rpm_2)^3} = \frac{(N_1)^3}{(N_2)^3} \tag{1.1}$$

$$\frac{Torque_1}{Torque_2} = \frac{(rpm_1)^2}{(rpm_2)^2} = \frac{(N_1)^2}{(N_2)^2} \tag{1.2}$$

Based on the equation 1.2, the relationship between consumed power (hp) and speed motor (rpm or N) is shown clearly in figure 1.3.

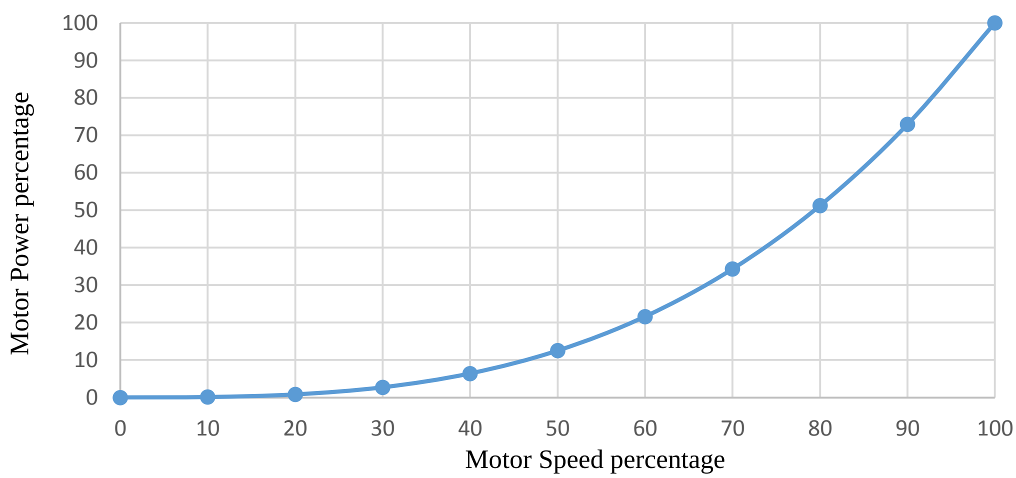


Figure 1.3 Relationship between Power and Speed

1.4 Thermal House Model

If we want to make our house more efficient at repelling the unpleasantness outdoors (weather conditions), what should we do first? Insulate walls? Insulate ceiling? Insulate roof? Better designing and choosing materials for windows? What has the biggest effect on house parts? To do understand heat transfer from a physics/engineering perspective, we can walk through some insightful calculations and using the physical components in SIMULINK MATLAB. Therefore, we will build a fantasy house model to evaluate the perfect type of using materials and appropriate thickness for roof, walls and windows.

1.5 Research Objectives

The thesis aims to upgrade the heat load model and to simulate the thermal profile of a residential building. At this time, we will integrate the house heat model with VFD air conditioning model. Then, we will associate the heat model with the VFD heating ventilation and air conditioning (HVAC) electrical for simulation and validation purposes. The simulation will be followed by comparison and analysis of energy consumption of both VFD and ON/OFF cycle air conditioning technologies.

The main objectives in this work can be summarized into five points:

- Upgrade and simulate the heat load model of a house located in Dhahran area at KFUPM campus.
- Integrate the upgraded heat load model with the ON/OFF cycle air conditioning model.
- Integrate the upgraded heat load model with the VFD driven air conditioning model.
- To validate the integration of upgrade heat load model for ON/OFF both cycle and VFD air conditioning systems by simulation.
- Collection of energy consumption measurement taken from VFD HVAC system and ON/OFF cycle HVAC system.

- Analysis and assessment of the energy consumption using simulation and measurement data will be compared for both systems.

1.6 Thesis Outline

Chapter 2 of the thesis presents a summary of the related literature. Chapter 3 develops a residential thermal model. Mathematical formulation of HVAC systems is given in Chapter 4. Simulation results and discussion for consuming power for ON/OFF and VFD HVAC system are presented in Chapter 5. Chapter 6 presents the experimental setup for two actual units, one by ON/OFF technique and the second unit by VFD technique. Validate real data and simulation results present in Chapter 7. Finally, Chapter 8 concludes the salient findings of this research and future recommendations.

CHAPTER 2

LITERATURE REVIEW

2.1 Thermal Model

Making a series of thermal models to describe the form of temperature variation within buildings is described in [4]. This would then be used to gain information about the buildings physical properties and the methods of heat generation. To do this, empirical models with adjustable parameters were developed to account for the suspected leading order terms in heat loss and production within the building. Heat losses were modelled in terms of convection and conduction by heat exchange with the environment and with other compartments. They extended the model to take account of incident solar radiation, which was observed to have a small but measurable effect on the form of the temperature variation. An optimum start controller using parameters extracted in real-time from measured data is described [5]. The five parameters are those characterizing the thermal responses of a building in terms of a second-order RC network. After showing that the algorithm is capable of obtaining similar parameter values as procedures reported previously. The performance of the system is demonstrated in a working school, where the boiler firing times were controlled for six weeks. The concept of using simulation as a tool for performance validation and energy analysis of HVAC systems is presented in [6]. They described one way of making use of this new technology by applying simulations, configured to represent optimum operation; to monitor data. The idea is to use simulation predictions as performance targets with which to compare monitored system outputs for performance validation and energy analysis. They presented results from applying the concepts to a large dual-duct air-handling unit installed in an office building in San Francisco. Evaluation the thermal and energy performance are developed using numerical model application [7]. Specific regulation equipment are used at office building to test its toughness. Estimation of requiring energy to get coziness level was developed by using Matlab/Simulink depending on the predict temperature variation [8]. They compared their results with IEA Building Energy Simulation Test (IEA BESTTEST) results. In addition, they validated their results in comparison with actual metered residential load data. Simple-physically-based model are used to simulate heating and electric energy consumption through year for domestic HVAC systems [9]. They depend on thermodynamic and heat transfer to regulate air volume in the household. Matlab easily simulates diver scenarios to implement model. A validation against actual metered residential load data provided by American Electric Power (AEP) is provided. Recognize the thermal model of house is used by autoregressive model with external inputs or with exogenous inputs (ARX model) [10]. They obtained the prediction state of the HVAC system. The proposed method is validated by experimentation in a particular home using GE Nucleus energy management system for data aggregation and algorithm implementation. ARX model and thermostat regulator are used to simulate and validate their data. Numerical load information, with load heterogeneity and versions for second-order dynamics equations are effectively essential for aggregated model [11]. They used new strategy for control to get accurate simulations by GridLAB-D. Extensive simulation results indicate that the proposed approach can effectively manage a large number of air conditioning systems to provide various demand response services, such as frequency regulation and peak load reduction. A residential space-conditioning system based on sensible heat transfer modeling using energy optimal control has been presented in [12]. They found that proportional control is advantageous to the two positions control for thermal comfort and energy efficiency but much deference in energy consumption. The Passive-House experimental project building details and the observing data outcomes within the tested period has been presented in [13]. Comparing the demand of cooling system from the simplified Global Sustainability Assessment System (GSAS) Energy Calculator model with the elaborated Dynamic-Simulation-Model (DSM) also has been offered. Neither model can handle the thermodynamic and fluid dynamic processes of the active insulation. An independent model is used to calculate the heat-transfer coefficient of the dynamically insulated walls, validated experimentally and then coupled with the energy models. The discrepancies in the predicted annual cooling demand between the simplified and detailed models did not exceed 15% for both static and dynamic operations of the Passive-House. Energy assessors can use GSAS Energy Calculator to predict the annual cooling demand with more confidence to demonstrate buildings compliance. Energy models should account for in-use factors to allow for differences in practical installation and performance compared to the laboratory test conditions for selected systems and technologies, which require field trials.

2.2 Electrical Model

Variable frequency/speed operation of the compressor and blower in central air conditioning system will allow the compressor speed to match the cooling capacity of the cooling load of the residence. The airflow rate is proportional to the speed of the air blower. The airflow rate is varied in time with the capacity, maintaining dehumidification capacity and taking advantage of the speed cubed power law. The resultant of using variable frequency/speed drives in the air conditioning system is to increase the Seasonal Energy Efficiency Ratio (SEER) by 30%-40% compared to a system with ON/OFF cycle capacity control, which reflect on electric energy saving [14]. A VFD system can provide energy saving benefits, improved comfort control and lower blower noise levels. Energy saving technologies for inverter air conditioners has been reviewed in [15]. They presented the technology trends and the latest energy efficient technologies for compressor motor and power converter. Most applications for VSD systems involve variable torque loads—such as fans and centrifugal pumps-where the load power varies as the cube of the speed are discussed in [16]. Performance tests of VSD systems are planned to measure efficiency of the VSD unit and the efficiency of the involved motor. While efficiency is a magic word, the real benefit of VSD systems is the reduction of energy used to provide the quantity of product (fluid or air) of the pump or fan. Next, they considered that many user companies applied their motors to operate at 80% nameplate rating at rated speed. That means that the required hp per speed is now 80% of motor nameplate rating and the cubed curve effect. In effect, a $100-hp$ motor is operated at $80\ -hp$ for rated speed. Other operating plans will call for a new set of motor ratings for various speeds. Operating modes will surely change the apparent results. Maximum savings from use of VSD systems will occur where maximum times are spent operating at speeds that range below the 75% level for many hours per year. Industrial sectors and researchers have focused their attention on energy saving technology and promoted the development of high efficiency products. One of the devices used in the VSD is brushless DC motor in compressor due to high efficiency through wide range of motor speed. The actual motor positions to commutate the motor current adequately. Depending on the inability of the Hall position sensors to work well due to high-temperature-environment of refrigerants, sensor-less control patterns play an important part in the applications of inverter-fed-BDCM compressors [17]. They analyzed the sensor-less circuits with many details to find the best design rules of the parameters for several compressor motors. In addition, they limited the sensor-less control circuits to improve a practical operation controller for BDCM-Compressors. A dual-mode control strategy for BLDC motor drivers with power-factor-correction (PFC) are proposed to use in high-efficiency-compressor applications in [18]. They developed modern control strategies PAM mode and PWM mode with reduced switching frequency for efficiency optimization of the compressor motor drive to maintain a constant V/Hz ratio with specified current ripples. Based on their control system, innovative PWM control structures can be developed to improve the inverter efficiency and reduce the motor audio noise by controlling the PWM duties to achieve specified phase current profile. Modelling the induction motor with a variable frequency drive are presented in [19]. They simulated and analyzed the working performance for model by using MATLAB/SIMULINK. The model achieved the control of the speed of the induction motor from zero to the nominal speed by varying the frequency of the applied ac voltage using pulse width modulation method.

2.3 LabVIEW Module

Thermal model of building has a special importance for assessment and online evaluation since the air conditioning load is consistently varying, the efficient energy consumption became a priority. Monitoring and controlling process variables (PV) such as Temperature, Pressure, Flow and Level Control in system are build using LabVIEW [20]. The corresponding PV values are measured and converted into Digital Signals using NI-DAQ and these are controlled in LabVIEW. A temperature measurement module using DS18B20 digital temperature sensor is developed to work as a standalone system [21]. The module is compared with other conventional temperature sensors used in space applications. A temperature and humidity monitoring system is constructed [22]. A set of software by LabVIEW language is compiled. The program is operated in a circular manner and automatically. a temperature measurement and control system for constant temperature reciprocator platelet preservation box is designed based on Fuzzy-PID control [23]. The humidity and temperature in ammunition storehouse is very important to the quality of ammunition during storage is applied in [24]. They improved the management efficiency of the storekeepers in storehouse, and designed a monitored system of temperature and humidity for ammunition storehouse based on LabVIEW. Development a system to record and analyze parameters like wind speed, wind direction, pressure and temperature using LabVIEW is reported [25]. Interfacing is done using data acquisition system. In addition, current and voltage from utility feeder are also monitored to measure power and power factor. Based on the improved traditional steady-state method which combined with LabVIEW virtual system in measuring of the thermal conductivity of poor conductor, the minutely monitoring of temperature on the two surfaces of a sample is realized [26]. A multifunctional virtual power quality monitoring system is designed and implemented in LabVIEW environment [27]. The root means square (RMS) value, the waveforms of three-phase voltage and current, the harmonic components, the total harmonic distortion (THD) and S-transform analysis waveforms of the three-phase voltage and current signals can be calculated and displayed in the system. In this paper, a performance monitoring and experimental test system for measuring metrological parameters and electrical parameters for HVAC system is proposed. Automatic data acquisition, DAQ, technology made by National Instrument (NI) is used as hardware for monitoring the HVAC system performance. The software of the data acquisition system based on LabVIEW package is used to display, store, and process the collected data in the PC-hard disk. The objective of this research is to develop a platform for standalone PV monitoring system to collect the data and evaluate the performance.

CHAPTER 3

RESIDENTIAL THERMAL MODEL

3.1 Methodology and Definitions

3.1.1 Gas Laws

The gas laws absolutely contract with how gases perform with respect to pressure, volume, temperature, and amount. Expansion and compression gas causes decrease and increase temperature and pressure respectively, so the relation between pressure (P) and volume (V) is an inverse relationship. The relation at constant temperature (T) is explained in figure 3.1. The figure usually is called as isotherm and is an equilateral (or the rectangular) hyperbola.

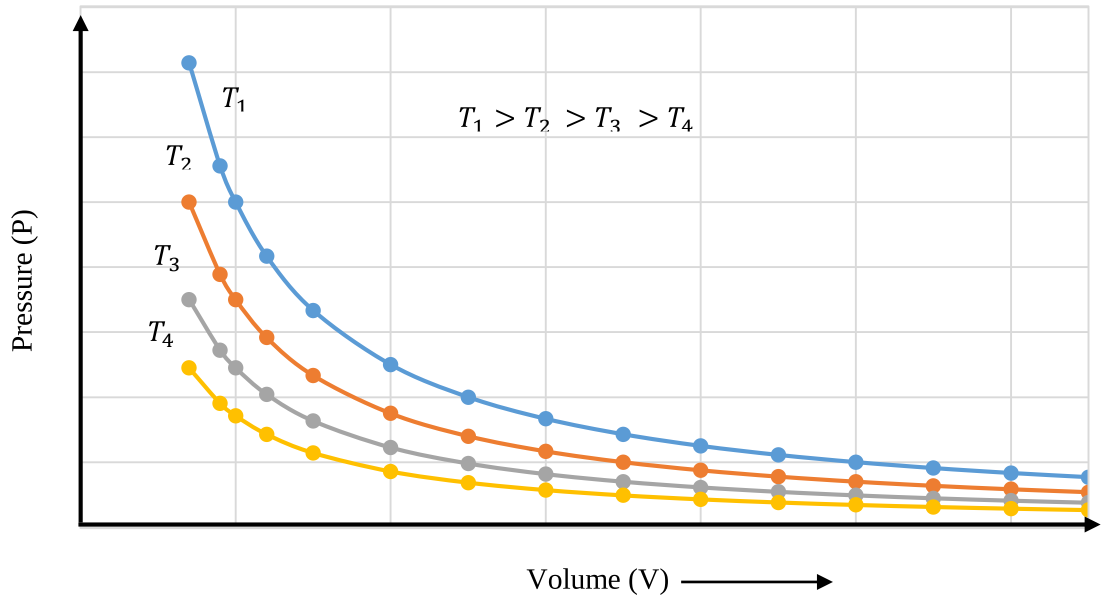


Figure 3.1: The Isotherms Curve for an Ideal Gas

3.1.2 Heat and its Types

Transferred energy due to temperature variance is defined as heat. It simply passes energy from a warm object to a cold object. In addition, it is the flow of energy from a high temperature body to a lower temperature body. SI unit of the heat flow described as Watt, which is 1 J/s of flow. Measuring the capability of a material, or any thermal system, to pass heat energy to other thermal system is called temperature. Btu and Calorie are other definition heat energy where are amount of heat needs to raise 1Ib and 1 gram of water by 1°F and 1℃ or 1K respectively.

The amount heat required to increase temperature is described by:

$$Q = c_p \, m\Delta T \tag{3.1}$$

Moreover, the produced work is expressed by

$$W = FL \tag{3.2}$$

$$or\ by \quad W = PAL \tag{3.3}$$

which are the mechanical work and work applied by pressure and volume respectively [28].

Where,

Q: Amount of heat (kJ)

c_p: Specific heat (kJ/kg.K)

m: Mass (kg)

ΔT: Temperature difference between hot and cold side (K)

W: Amount of mechanical work (Nm (J)), 1 J = 1 Nm

F: Applied force (N)

L: Length or distance moved (m)

P: Applied pressure (N/m2 (Pa))

A: Pressurized area (m2)

3.1.3 Heat Transfer

Three main ways manage the transferred heat energy through or between substances i.e., convection, conduction and radiation are the basic heat transfer methods as shown in figure 3.2.

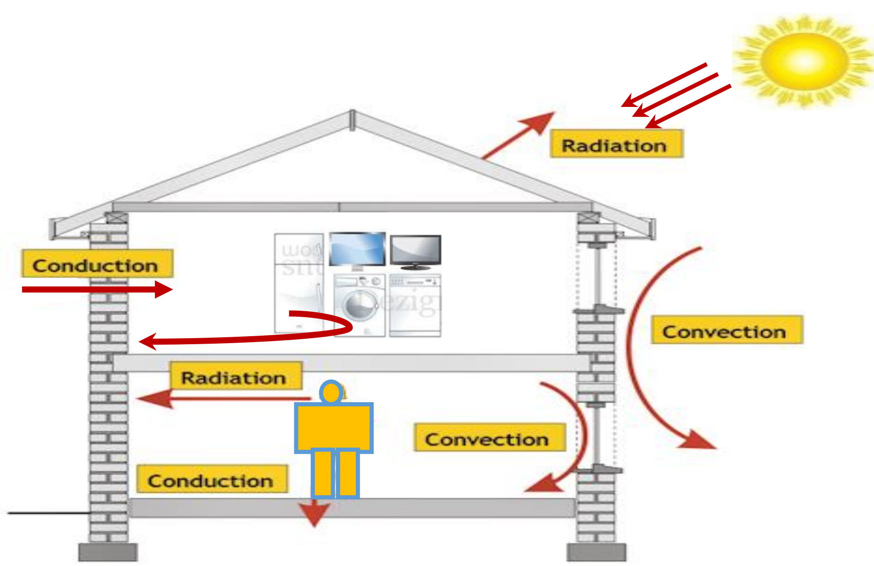


Figure 3.2 Heat Transfer Methods [convection, conduction and radiation]

Convection: transferred heat between a solid surface and other movement substance (gas or liquid) is called as convection heat where rating heat flow depend on moving temperature substance and on its flow rate.

$$Q_{\mathrm{conve}} = k_{conve}.\mathrm{A}.(\mathrm{T_A} - \mathrm{T_B}) \tag{3.4}$$

Where,

Q_{conve} : Convective heat flow
k_{conve} : Convection heat transfer coefficient
A : Surface area
$\mathrm{T_A}, \mathrm{T_B}$: Temperature of the bodies

Conduction: transferred heat internally via conduction substances without flow by movement atoms of substance carrying heat energy from part to another is defined like conductive heat energy.

$$Q_{\mathrm{cond}} = k_{cond}.\frac{\mathrm{A}}{\mathrm{D}}.(\mathrm{T_A} - \mathrm{T_B}) \tag{3.5}$$

Where,

Q_{cond} : Conductive heat flow
k_{cond} : Material thermal conductivity
A : Area normal to the heat flow
D : Distance between the layers
$\mathrm{T_A}, \mathrm{T_B}$: Temperature of the bodies

Radiation: transferred heat occurs when heat transferred in form or like electromagnetic waves. This energy originates from a hot object travels freely during transparent media.

Depending on the surface and its temperature, the amount of radiation energy directly effects. The transfer heat function is ruled by the Stefan-Boltzmann law and is defined as following equation [29].

$$\mathrm{Q_{rad}} = k_{rad}.\,\mathrm{A}.\left(\mathrm{T_A}^4 - \mathrm{T_B}^4\right) \tag{3.6}$$

Where,

Q_{rad} : Radioactive heat flow

k_{rad} : Radioactive heat transfer coefficient

A : Surface area

$\mathrm{T_A}, \mathrm{T_B}$: Temperature of the bodies

In a real-world situation, we should deal with all three thermal paths simultaneously. So, let us consider a wall situated between a cold interior and a hot exterior. From experience, the wall will be a little cool to the touch, so we have thermal flow from the outer surface wall to the room via the convection and the radiation. The wall itself conducts heat to the inside surface. Then convection and radiation carry heat away from there. In equilibrium (and since thermal energy is not being created or destroyed in the wall), we have a balance of equations such that:

$$P_{conv,in} + P_{rad,in} = P_{cond} = P_{conv,out} + P_{rad,out} \tag{3.7}$$

Figure 3.3 shows the sum of the two input powers, which equals the conducted power that matches the sum of the output powers.

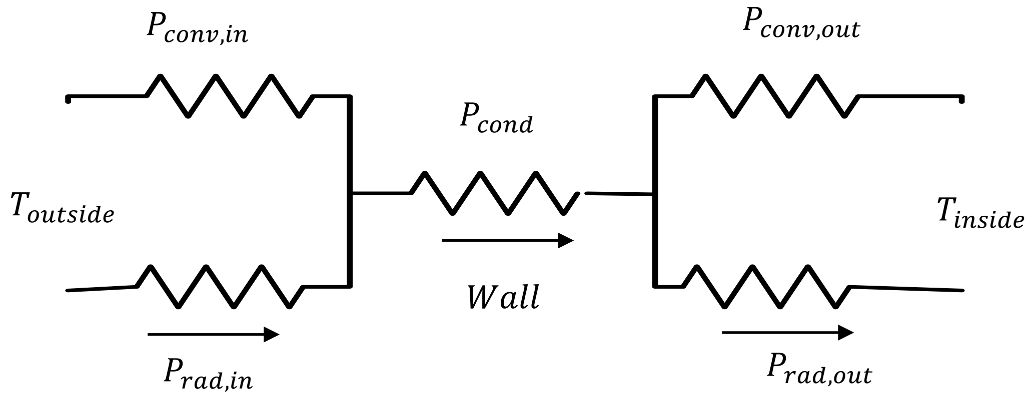


Figure 3.3 Equivalent Circuit of Power Heat low

3.2 Thermal Resistance

The concept of thermal resistance can be utilized to solve steady state heat transfer problems that involve series, parallel or combined series-parallel components. This article demonstrates how to calculate the total thermal resistance for such systems and how to calculate the thermal resistance for practical geometries such as a plane wall. Thermal resistance is the resistance of a particular medium or system to the flow of heat through its boundaries and is dependent upon geometry and thermal properties of the medium such as thermal conductivity.

Accurate knowledge of the thermal resistance for a given system or system component may permit calculation of the heat flow through it or the temperatures on its boundaries. This is of particular use in thermal design problems in industry such as calculating the heat loss from a tank or the selection of piping insulation.

3.2.1 Thermal Resistance Network

Thermal resistance networks employed in order to analyze steady state heat transfer. Thermal resistance networks have a similar functionality to electrical resistance networks used in electrical engineering and allow for easy calculation of the total thermal resistance in a system whether it is composed of resistances in series, parallel or both [30]. Three connections of thermal resistances network are explained in the following points.

1. Resistances in series

Often one must consider heat transfer through various mediums in series, one such example is the heat flow (Q) from a gas on one side of a planar wall to the gas on the other side. This heat transfer system is analyzed using the series thermal resistance network. The series network for both convection and conductive resistances is presented in figure 3.4.

$$Q = \frac{T_{\infty 1} - T_1}{R_{conv1}} = \frac{T_1 - T_2}{R_{wall}} = \frac{T_2 - T_{\infty 2}}{R_{conv2}} \tag{3.8}$$

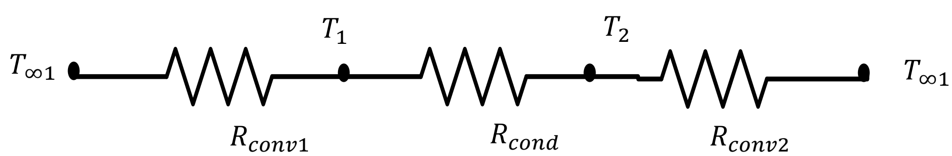


Figure 3.4: The Series Thermal Resistances Network

The total resistance for the system described above may be calculated from all the component resistances R_{conv1} , R_{wall} and R_{conv2} as follows.

$$R_{total} = R_{conv1} + R_{wall} + R_{conv2} \tag{3.9}$$

Once the total resistance has been calculated the heat flow through the system may be calculated from knowledge of the two end temperatures as follows.

$$Q = \frac{T_{\infty 1} - T_{\infty 2}}{R_{total}} \tag{3.10}$$

2. Resistance in parallel

Heat transfer may also occur through resistance in parallel, for example, the heat lost from the outer surface of a tank will occur due to both the convective and radioactive heat transfer mechanisms. Figure 3.5 displays the parallel connection for convective and radiative heat transfer mechanisms.

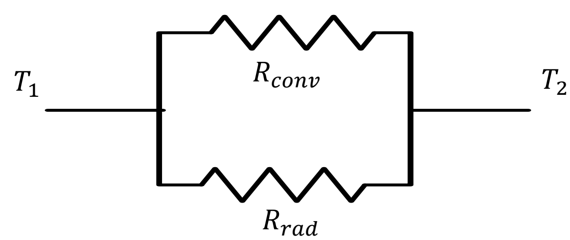


Figure 3.5 The Parallel Thermal Resistances Network

The inverse total resistance for the system shown above will be calculated by adding the inverses resistance of the two components.

$$\frac{1}{R_{total}} = \frac{1}{R_{conv}} + \frac{1}{R_{radl}} \tag{3.11}$$

This can simplify so it can be directly combined with the thermal resistances from other components in a given system that is of particular importance when thermal resistances exist in both parallel and series.

$$R_{total} = \frac{R_{conv} \ + \ R_{rad}}{R_{conv} \ \times \ R_{rad}} \tag{3.12}$$

3. Combined series and parallel resistance

In industrial heat transfer problems, thermal resistance is often in both series and parallel. For example, the heat loss from the contents of an un-insulated tank will have the convective resistance of the tank contents followed by the conductive resistance of the tank walls in series followed by convective and radiative resistance to the surround environment in parallel. This example described by the thermal resistances network in figure 3.6.

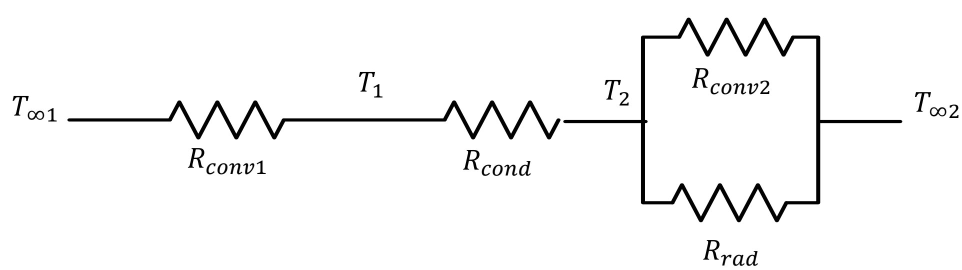


Figure 3.6 The Combined Thermal Resistances Network

In this instance, the total resistance is calculated by adding the total resistance for the series segment and the total resistance for the parallel segment as it described in the previous sections.

$$R_{total} = R_{conv1} + R_{wall} + \frac{R_{conv2} \times R_{rad}}{R_{conv2} + R_{rad}} \tag{3.13}$$

3.2.2 Calculation of Thermal Resistances

In the design of industrial equipment, thermal resistances are required to determine a steady state temperature at some point along a thermal resistance network, for example the temperature between a tank wall and the inside of its insulation [30].

In order to determine these temperatures one must first calculate the thermal resistances. Some equations for the calculation of thermal resistance are presented in next sections.

1. Conductive Resistance

Conductive resistance equations for some common cases are outlined in the equations below.

Geometry	Resistance Equation	
Plane Wall	$R_{wall} = \frac{x}{kA}$	(3.14)
Cylinder Wall	$R_{cyl} = \frac{ln\left(\frac{r_2}{r_1}\right)}{2\pi Lk}$	(3.15)
Spherical Wall	$R_{sph} = \frac{r_2 - r_1}{4\pi r_1 r_2 k}$	(3.16)

2. Convective Resistance

The resistance to heat transfer via convection is calculated by the following equation.

$$R_{conv} = \frac{1}{hA} \tag{3.17}$$

In order to calculate the convective resistance, the heat transfer coefficient, h must first be determined. Many correlations exist to calculate the heat transfer coefficient depending on of the geometry of the system is considered.

3. Radiative Resistance

The resistance to heat transfer via radiation is calculated by the following equation:

$$R_{rad} = \frac{1}{h_{rad}A} \tag{3.18}$$

This allows radiative heat transfer to be easily grouped together with other heat transfer modes when considering total heat transfer for a given system; however, the radiative heat transfer coefficient must first be calculated.

Where,

R : Thermal resistance (K/W)

R_{conv} : Thermal resistance for convective heat transfer (K/W)

R_{rad} : Thermal resistance for radiative heat transfer (K/W)

R_{cond} : Thermal resistance for conductive heat transfer through a plane wall (K/W)

Q : Heat flow (W)

T : Temperature at a given point (K)

X : Thickness of a plane wall (m)

A : Heat transfer area (m^2)

K : Average thermal conductivity (W/m.K) r1 : Internal diameter (m)

r2 : External diameter (m)

L : Length of a pipe (m)

h : Heat transfer coefficient ($W/m^2.K$)

3.2.3 Heat Flow with Combined Thermal Resistances Conduction, Convection and Radiation

We can now analyze problems in which both conduction and convection occur, starting with a wall cooled by flowing air on each side [31]. As discussed, a description of the convective heat transfer is given explicitly as:

$$\frac{\dot{Q}}{A} = h_1(T_\omega - T_\infty) \tag{3.19}$$

This could represent a model of a plane wall with internal cooling. Figure 3.7 shows the configuration of roof/wall/window section.

Transfer heat from inner surface wall/roof/windows to inside house air explained in figure 3.7, which is given by equation 3.20.

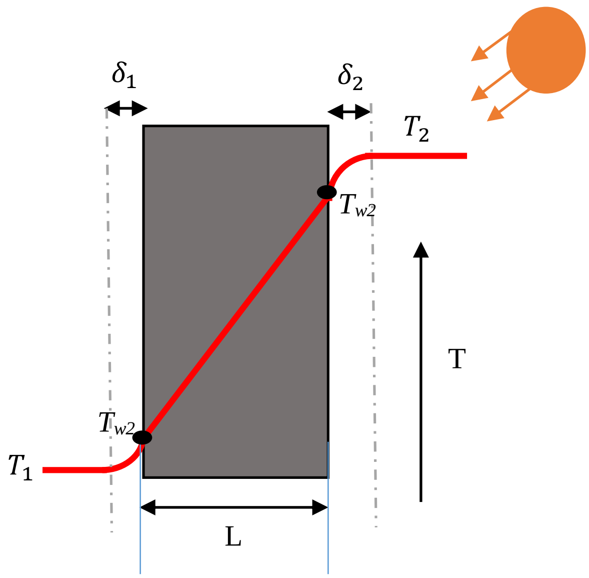


Figure 3.7 Convective-Conductive Roof, Wall and Windows with Heat Transfer

$$\frac{\dot{Q}}{A} = h_1(T_{W1} - T_1) \tag{3.20}$$

Which is the heat transfer per unit area to the inner air. The heat transfer from outside air to wall/roof/windows is combined of convective and radiative resistances, which is connected in parallel ($R_{conv} \mathbin{/\!/} R_{Rad}$) and it is given by next equation to present the heat flow:

$$\frac{\dot{Q}}{A} = (h_2 + h_{rad})(T_2 - T_{W2}) \tag{3.21}$$

Across the wall, we can get the heat transfer from outside wall to inside wall as a conductive heat by:

$$\frac{\dot{Q}}{A} = \frac{k}{L}(T_{W2} - T_{W1}) \tag{3.22}$$

The quantity $\dot{Q}/A$ is the same in all of these expressions. Putting them all together to write the known overall temperature drop yields a relation between heat transfer and overall temperature drop, $(T_2 - T_1)$:

$$(T_2 - T_1) = (T_2 - T_{W2}) + (T_{W2} - T_{W1}) + (T_{W1} - T_1) = \frac{\dot{Q}}{A}\left[\frac{1}{h_1} + \frac{L}{k} + \frac{1}{h_2 + h_{rad}}\right] \tag{3.23}$$

We can define a thermal resistance, R_{total}, as before, such that

$$\dot{Q} = \frac{(T_2 - T_1)}{R_{total}} \tag{3.24}$$

Where, the total thermal resistance (R) is given by:

$$R_{total} = \left[\frac{1}{Ah_1} + \frac{L}{Ak} + \frac{1}{A(h_2 + h_{rad})}\right] \tag{3.25}$$

Equation 3.25 reflected the thermal resistance for a solid wall with convection heat transfer on each side.

For a plane wall in a house model, inside house temperature is a critical consideration. In terms of figure 3.7, T_2 is the out-house temperature and T_1 is the in-house temperature. We wish to find T_{W2} because this is the highest temperature to outside surface house (walls, roof or windows) and the inside surface house temperature T_{W1} . From equation 3.24, the outside surface temperature is written as:

$$T_{W2} = T_2 - \frac{\dot{Q}}{A(h_2 + h_{rad})} = T_2 - \frac{(T_2 - T_1)}{R_{total}}\left[\frac{1}{A(h_2 + h_{rad})}\right] \tag{3.26}$$

Using the expression for the thermal resistance, the wall temperatures can be expressed in terms of heat transfer coefficients and wall properties as

$$T_{W2} = T_2 - \frac{(T_2 - T_1)}{\frac{(h_2 + h_{rad})}{h_1} + \frac{L(h_2 + h_{rad})}{k} + 1} \tag{3.27}$$

Similarly, we can get T_{W1} by:

$$T_{W1} = T_1 + \frac{(T_2 - T_1)}{\frac{h_1}{h_2 + h_{rad}} + \frac{Lh_1}{k} + 1} \tag{3.28}$$

Equation 3.27 provides some basic design guidelines. The goal of this is getting a value of T_{W1} close to disired temperature inside house. It means h_1 should be large, k should be small and L should be large (which mean using many layer for insulation).

❖ **The Upgraded Heat Model Using Three Layers for Roof and Wall**

In most climates, insulation is needed for all sides of a house: under the slab or lowest conditioned floor, at the basement walls, at the above-grade walls, and at the ceiling or roof. Because different insulation materials are good at doing different things, it makes sense to choose insulation based on the job it has to do. Heat flow is only part of the equation; moisture, air leakage, and drying potential are also important considerations.

Figure 3.8 shows how we can find the temperature at each desired point at surface or center of plaster, concrete, outside wall plaster or stucco. This will help us to calculate the suitable material with its thermal conductivity (k) and the appropriate thickness (L).

Upgraded the model components for second order heat system are explain in the chapter 4. The aim of this section is improve the parameters such as type of building materials and thickness depending on the desired temperature in house. This means that at any instant the model able to represent the thermal aspects of a building in its present condition, thus allowing predictions to be made.

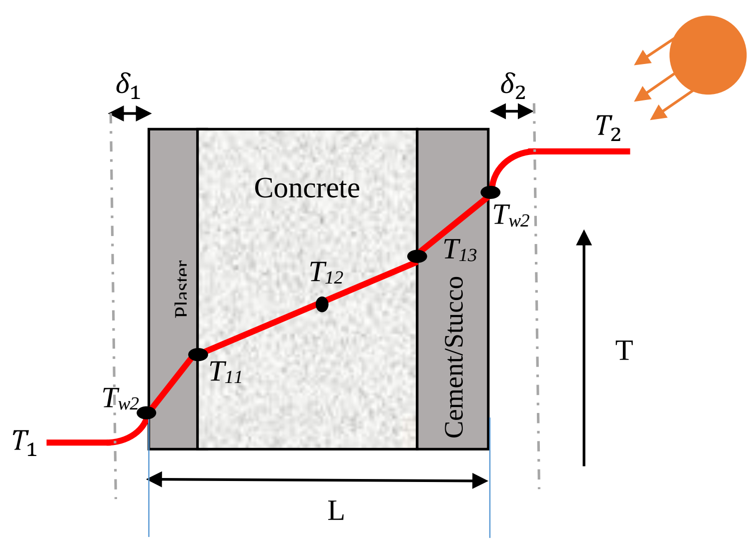


Figure 3.8 Convective-Conductive Roof, Wall and Windows with Three Layers and Heat Transfer

3.3 HVAC Cycle

Controlling air quality, cooling/heating air for domestic, commercial and manufacturing buildings are performed by Heating, Ventilation and Air Conditioning system. They kept up good internal air quality and deliver thermal comfort. The designing and selection of the HVAC system types generally effect on performance goals, therefore, classification HVAC systems depends on provided heat or cooling methods such as, ducted air system, water system, radiant system, etc. or sometimes on type of cooling as electric conditioner, electric pump, chiller, gas conditioner, etc. In addition, HVAC can also sort to ventilation type for instance intake louvers and fans, supply and return air system, dedicated ventilation system, etc. [32].

Air-conditioning is a device that moves heat from place to another. Its performance done through movement a heat from inside area to outside. This process is done through operation called refrigeration cycle. The cycle defines as thermodynamic cycle, which relate to change temperature, humidity and pressure inside and outside areas. According to the location of air-conditioning pieces, cooling and vapor units, we can typed air-conditioning systems as wind system, split system, central system, etc. but the location don’t effect on refrigeration cycle operation.

According to basic thermodynamic operation, flowing heats from warmer to cooler area, the refrigeration cycle of air conditioning classifies to four steps, so let us describe each of them. Figure 3.9 explains the refrigeration stages.

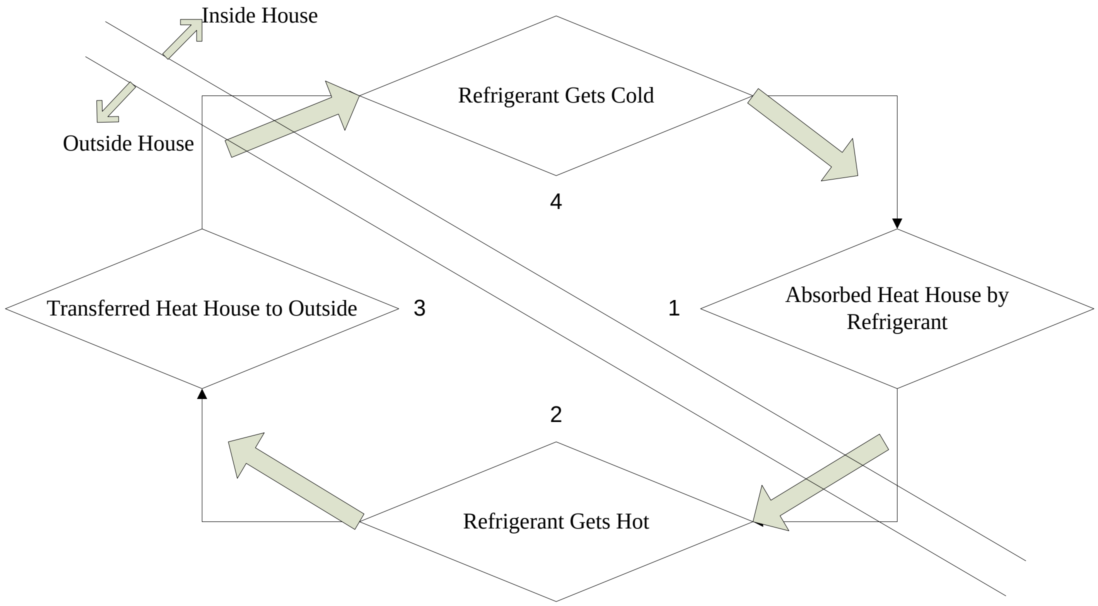


Figure 3.9: The Refrigeration Cycle

Stage 1: Catching heat.

Pull warm heat from inside house and pass it through very cold copper coils. The basic behavior at this point is that heat energy prefers to flow from warmer area to cooler area. Therefore, air temperature has dropped through pass it by these coils. The dropping heat absorbs into copper coils and it converts the refrigerant substance into a vapor.

Stage 2: Refrigerant gets hot.

According to basic thermodynamic operation, flowing heat from hot to cold area, refrigerant substance is pumped to increase pressure that cause rise temperature by compressor, where compressor is located outdoor.

Stage 3: Refrigerant dives up its heat to the outdoor air.

Expel the refrigerant heat from outdoor unit to the surrounding air by using fan, which is located inside this unit. Flowing heat from outdoor pipes or tubes are caused to condense vapor refrigerant and then converting it into liquid.

Stage 4: Refrigerant gets cold

Expanding the refrigerant substance warm, which passes from third stage, into a greater volume, which are occurred by a special device. This expansion causes to drop a lot of the refrigerant substance temperature [33].

3.4 House Heating-Cooling loads

3.4.1 Heating-Cooling Loads - Latent and Sensible Heat

The design cooling load (or heat gain) is the amount of heat energy to be removed from a house by the HVAC equipment to maintain the house at indoor design temperature when worst case outdoor design temperature is being experienced [34] . There are two types of cooling loads:

- Sensible cooling load
- Latent cooling load

The sensible cooling load refers to the dry bulb temperature of the building and the latent cooling load refers to the wet bulb temperature of the building. In the summer, humidity influence in the selection of the HVAC equipment and the latent load as well as the sensible load must be calculated.

- **Factors that influence to the sensible cooling load:**

- Glass windows or doors
- Sunlight striking windows, skylights, or glass doors and heating the room
- Exterior walls
- Partitions (that separate spaces of different temperatures)
- Ceilings under an attic
- Roofs
- Floors over an open crawl space
- Air infiltration through cracks in the building, doors, and windows
- People in the building
- Equipment and appliances operated in the summer
- Lights

Notice that below grade walls, below grade floors, and floors on concrete slabs do not increase the cooling load on the structure and are therefore ignored. Other sensible heat gains are taken care of by the HVAC equipment before the air reaches the rooms (system gains). Two items that require additional sensible cooling capacity from the HVAC equipment are:

- Ductwork located in an unconditioned space
- Ventilation air (air that is mechanically introduced into the building)

- **Sensible Heat Load and Required Air Volume Chart:**

Sensible heat load - heating or cooling - and required air volume to keep temperature constant at various temperature differences between entering air and room air based on equation 3.29 are indicated in figure 3.10 [34]:

➢ Factors that influence to the latent cooling load

Moisture is introduced into a structure through:

- People
- Equipment and appliances
- Air infiltration through cracks in the building, doors, and windows

Other latent heat gain is taken care of by the HVAC equipment before the air reaches the rooms (system gain).

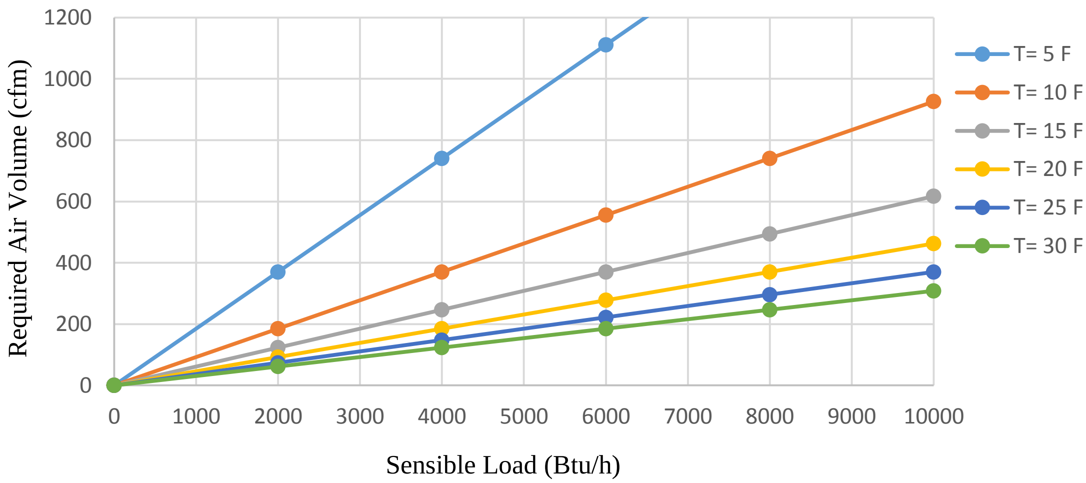


Figure 3.10 The Required Air Volume (cfm) for Sensible Load (Btu/h)

➢ Latent Heat Load and Required Air Volume Chart:

Latent heat load - humidifying and dehumidifying - and required air volume to keep temperature constant at various temperature differences between entering air and room air based in equation 3.30 are indicated in the figure 3.11 [34]:

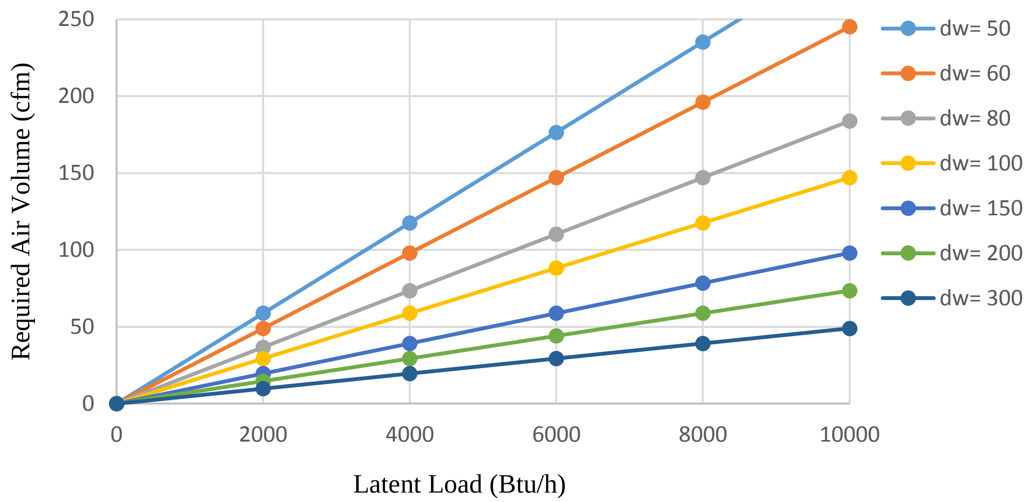


Figure 3.11: The Required Air Volume (cfm) for Latent Load (Btu/h)

3.4.2 Cooling-Heating Equations

Latent and sensible cooling and heating equations - in imperial units [35].

➢ <u>Sensible Heat:</u>

The sensible heat in a heating or cooling process of air (heating or cooling capacity) can be expressed as:

$$h_s = 1.08\, V\, dT \tag{3.29}$$

where:

h_s: Sensible heat $\left(\frac{\text{Btu}}{\text{hr}}\right)$

V: Air volume flow (cfm, cubic feet per minute)

dT: Temperature difference (°F)

- Latent Heat:

The latent heat due to moisture in the air can be expressed as:

$$h_l = 0.68\, V\, dw_{gr} \tag{3.30}$$

$$Or \quad h_l = 4840\, V\, dw_{lb} \tag{3.31}$$

Where:

h_l: Latent heat $\left(\frac{\text{Btu}}{\text{hr}}\right)$

V: Air volume flow (cfm, cubic feet per minute)

dw_{gr}: Humidity ratio difference (grains water/lb dry air)

dw_{lb}: Humidity ratio difference (lb water/lb dry air)

1 grain = 0.000143 lb = 0.0648 g

- Total Heat - Latent and Sensible Heat:

Total heat due to both temperature and moisture can be expressed as:

$$h_t = 4.5\, V\, dh \tag{3.32}$$

where:

h_t: Total heat (Btu/hr)

V: Air volume flow (cfm, cubic feet per minute)

dh: Enthalpy difference (btu/lb dry air)

Total heat is expressed as:

$$h_t = h_s + h_l = 1.08\, V\, dT + 0.68\, V\, dw_{gr} \tag{3.33}$$

❖ Illustration - Heating Air

An airflow of one cfm is heated from 32 to 52°F. Using (31) the sensible heat added to the air is expressed as:

$$hs = 1.08\,(1\,cfm)\,((52\,°\text{F}) - (32\,°\text{F})) = 21.6\,(Btu/hr)$$

3.5 Calculating Indoor Temperature and Humidity Loads

Indoor climate is influenced by:

- Sensible and latent heat from persons, lights, machines and electrical equipment and industrial processes.
- Pollution and gases from persons, building materials, inventory and industrial processes.

The most important sources influencing the indoor climate may be summarized to [36]:

1. sensible and latent heat from persons
2. sensible heat from lights
3. sensible heat from electric equipment
4. sensible heat from machines
5. miscellaneous loads

3.5.1 Sensible and Latent Heat from Persons

Sensible heat from persons is transferred through conduction, convection and radiation. Latent heat from persons are transferred through water vapor. The sensible heat influence on the air temperature and latent heat influence the moisture content of air. The heat transferred from persons depends on activity, clothing, air temperature and the number of persons in the building.

3.5.2 Sensible Heat from Lights

Heat transferred to the room from the lights is calculated as:

$$H_l = P_{inst} K_1 K_2 \tag{3.34}$$

Where:

H_l: Heat transferred from the lights (W)

P_{inst}: Installed effect (W), K_1: Simultaneous coefficient

K_2 : Correction coefficient if lights are ventilated. ($= 1$ for no ventilation, $= 0.3 - 0.6$ if ventilated)

Table 3.1 estimates heat load from lights [36]. (The manufacturer's datasheets should be checked for details)

Table 3.1 The Estimate Heat Load from Lights

Installed effect (W)	**Illumination (lux)**				
	200	**400**	**600**	**800**	**1000**
Incandescent lamp	38	75	110	145	180
Fluorescent tubes	15	25	36	48	60

The requirements for lighting levels in the rooms depend on the nature of the work in rooms. Table 3.2 shows the normal illumination of rooms [37]:

Table 3.2 Normal Illumination of Rooms

Office Activity	Illumination (lux)
Normal work	200
PC work	500
Archive	200
Drawing work, normal	500
Drawing work, detailed	1000

Sensible Heat from Electric Equipment

Heat transferred from electrical equipment can be calculated as:

$$H_{eq} = P_{eq} K_1 K_2 \tag{3.35}$$

Where:

H_{eq}: Heat transferred from electrical equipment (W)

P_{eq}: Electrical power consumption (W)

K_1 : Load coefficient

K_2 : Running time coefficient

3.5.3 Sensible Heat from Machines

When machines run, heat may be transferred to the room from the motor and/or the machine.

If the motor is in the room and the machine is on the outside - the heat transferred can be calculated as:

$$H_m = P_m / h_m - P_m \tag{3.36}$$

If the motor is belt driven and the motor and belt are in the room and the machine is on the outside - the heat transferred can be calculated as:

$$H_m = P_m/h_m - P_m * h_b \tag{3.37}$$

Where:

H_m : heat transferred from the machine to the room (W)

P_m : electrical motor power consumption (W)

h_m : motor efficiency

h_b : $belt\ efficiency$

If the motor and the machine is in the room - the heat transferred can be calculated as:

$$H_m = P_m / h_m \tag{3.38}$$

In this situation, the total power is transferred as heat to the room.

Note! If the machine is a pump or a fan, most of the power is transferred as energy to the medium and may be transported out of the room.

If the motor is outside and the machine is in the room - the heat transferred can be calculated as:

$$H_m = P_m \tag{3.39}$$

If the motor is belt driven and the motor and belt is outside and the machine is in the room - the heat transferred can be calculated as:

$$H_m = P_m * h_b \tag{3.40}$$

3.5.4 Miscellaneous loads (Carbon dioxide - CO_2)

Carbon dioxide (CO_2) concentration in "clean" air is 575 mg/m^3.Huge concentrations can cause headaches and the concentration should be below 9000 mg/m^3. Persons produce carbon dioxide during the combustion. The concentration of carbon dioxide in the air can be measured and used as an indicator of air quality. The respiration and CO_2 generation per person at work conditions are explained in Table 3.3 [37].

Table 3.3: The Respiration and CO_2 Generation per Person

Activity	Respiration per person (m^3/h)	CO_2 generation per person (m^3/h)
Sleeping	0.3	0.013
Sitting, relaxed	0.5	0.02
Working, moderate	2 – 3	0.08 - 0.13
Working, heavy	7 – 8	0.33 - 0.38

3.6 Variable Frequency Drive

VFD is a type of motor controller that drives an electric motor by varying the frequency and voltage supplied to the electric motor. Other names for a VFD are variable speed drive, adjustable speed drive, adjustable frequency drive and AC drive. VFDs extensively use in industry to deliver regulating speed control of AC motors. Though recent versions are moderately simple to isolate and operate, VFDs are quit complex, comprising a numerous of innovative hardware and software. VFD application and operation can be oven developed by empathetic internal VFD procedures. To that end, we explain the items used to define VFD interior operations and outside interfaces. Figure 3.12 displays three main components of VFD, a VFD's rectifier/converter accepts ac line voltage. Then its DC bus stores converted power on capacitor. Finally, it inverter creates desirable sinusoidal output.

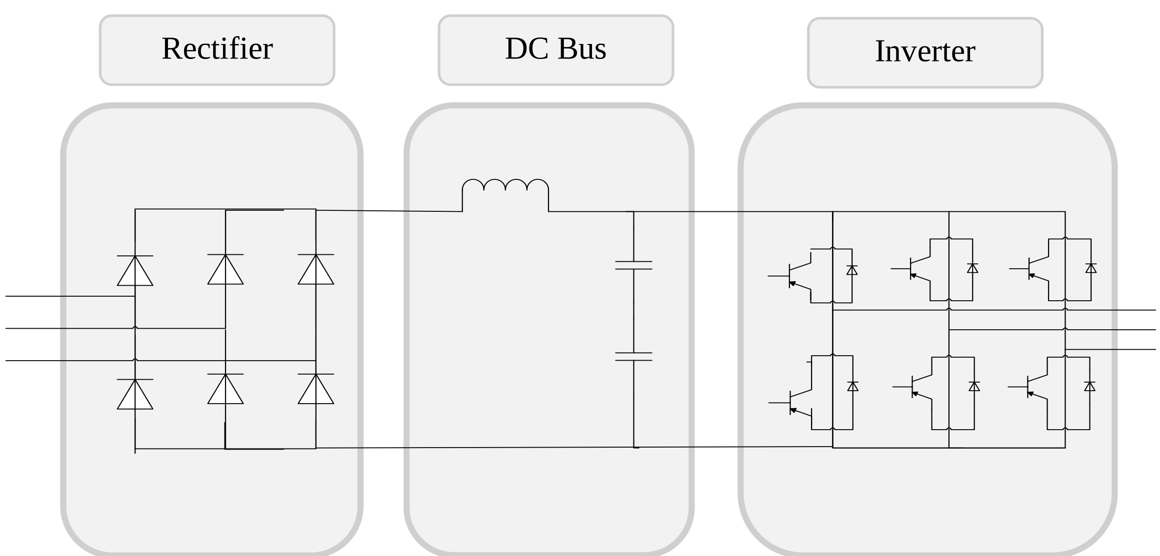


Figure 3.12 Three Main Components [Rectifier, DC Bus and Inverter]

3.6.1 Rectifier/Converter

One of the three primary sections of a VFD's main power circuit, and first in terms of power flow. Incoming AC line voltage is rectified to DC voltage in the converter section, which consists of diodes, silicon-controlled rectifiers (SCRs), or insulated gate bipolar transistors (IGBTs) connected in a full-wave bridge configuration.

3.6.2 DC Bus

The second primary section of a VFD's main power circuit, chiefly comprised of capacitors that store power rectified by the converter.

3.6.3 Inverter

The third and final primary section of a VFD's main power circuit. This section is comprised of IGBTs that create sinusoidal output current using pulsed dc bus voltage, or pulse width modulation (PWM). VFDs themselves are sometimes called inverters, as the presence of an inverter section is the primary difference between VFDs and dc drives.

3.7 Operation Load Profile

Heating/Cooling loads are the measure of energy that need to be added or removed from a residence by the HVAC system to provide the desired level of comfort air within a house. The appropriate VFD HVAC system begins with an accurate understanding of the heating/cooling loads on a house. The heating/cooling load calculation results will have a direct contact with the climate change, occupant behavior, economic status of occupants, physical properties of building and characteristic of heating system.

The Figures 3.13 and 3.14 explain the load operation through one hot day in Dhahran area. Figure 3.13 shows the outdoor temperatures which are measured for 24 H's and we can observe the temperature is started around 30 C^{o} and it goes up dramatically to 51 C^{o} at midday, then it drops slowly until came to 35 C^{o} at midnight. The daily house activity loads are displayed in figure 3.14, where it consists of two persons live in house, fluorescent 400 lux for light, kitchen tools (oven & fridge), computer, monitor, printer, and Wi Fi unit as shown in Table 3.4 [37].

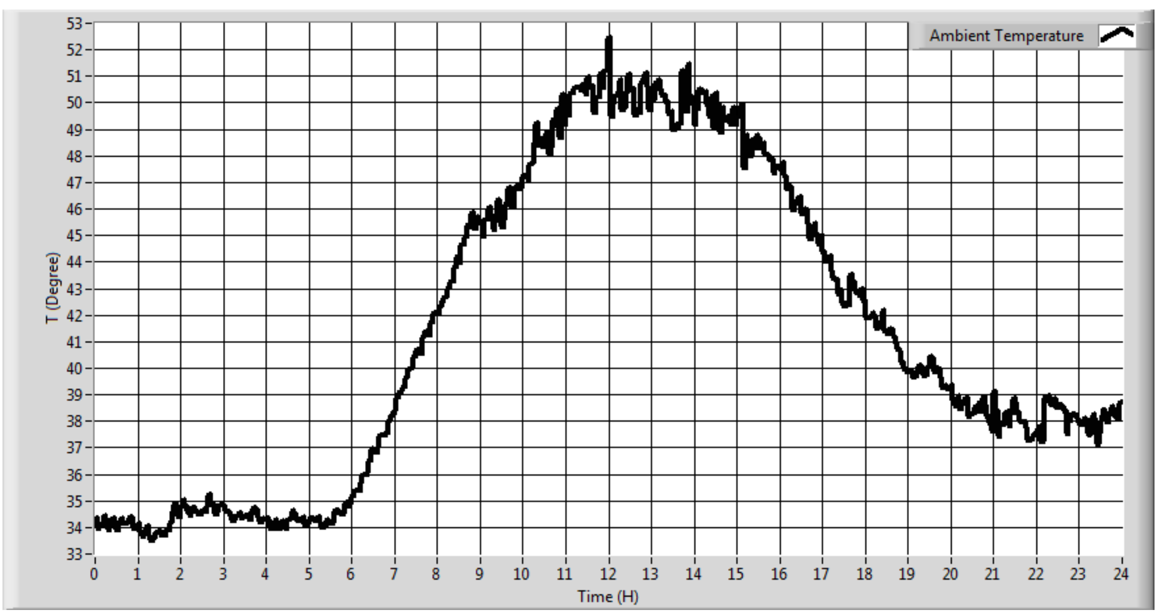


Figure 3.13: Daily Out-House Temperature

Table 3.4 Daily Internal Heat Load

Time (h)		1-7	8	9-13	14	15-18	19	20	21-24
2-persons	Male	80	120	120	120	120	120	120	120-80
	Female	68	195.5	102	195.5	102	102	195.5	102-68
Fluorescent 400 lux 15-20 w/m2	House area = 48.45 m^2	0	0	0	0	0	658.71	658.71	658.71
	Kitchen Area = 4.536 m^2	68.04	68.04	68.04	68.04	68.04	68.04	68.04	68.04
Computer (J/s)		150	150	150	150	150	150	150	150
Printer (J/s)		100	100	100	100	100	100	100	100
Monitor (J/s)		80	80	80	80	80	80	80	80
Wi-Fi Unit (J/s)		100	100	100	100	100	100	100	100
TV (J/s)		0	0	0	100	100	100	100	100
Oven (J/s)		0	1500	0	2500	0	0	2000	0
Fridge (J/s)		150	150	150	150	150	150	150	150

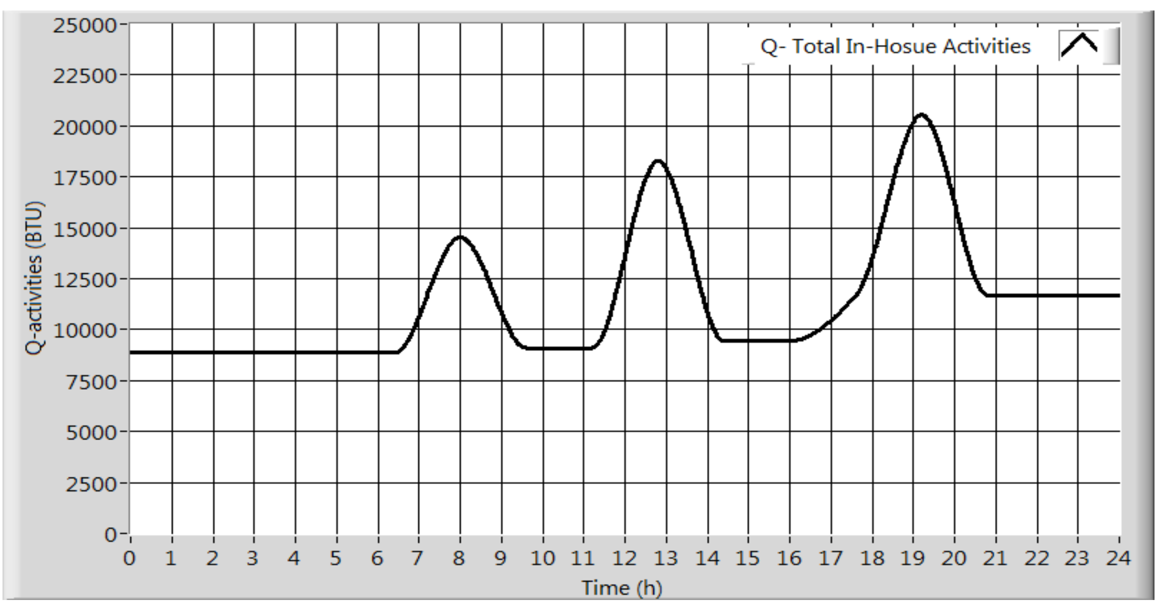


Figure 3.14 Daily Internal Heat Load

CHAPTER 4

MATHEMATICAL FORMULATION OF HVAC SYSTEMS

4.1 Introduction

When developing strategies to minimize energy consumption in buildings it is crucial to understand the dynamics working of heat energy generation and losses. This section aims to investigate some of the contributions heat generation and losses studied through the developed of number empirical models. From these models, a thermal model is derived to allow us build relation heat flows to the variations in temperature. The developed models will have adjustable parameters corresponding to different contributions of the heat budget by understanding the form of variation temperatures. Therefore, we aim to appreciate the most important factors in the energy consumption and production within the building.

Using thermal models in combination with natural data (e.g. raw temperature data from the building and data from weather stations) the objectives of the model are:

1. To infer thermal properties of the buildings primarily achieved by modelling the process of heat loss within a building.

2. To infer heat production (i.e. to make a virtual energy meter) primarily achieved by looking at possible models of contributions to heat production.

What might we expect this thermal model to look like? Well, we need to think about the most obvious causes of heat generation and loss within a building. Firstly, looking at cooling/heat losses, these is categorized into two forms, conduction and ventilation. Conductive heat losses can be thought of in terms of heat flowing from a hot region to a cold region through windows and walls. Ventilation meanwhile represents the direct movement of hot air out of a building through cracks and gaps as well as through deliberate ventilation.

The standard method of modelling heat losses is making relation for both heat flows and the difference temperature between the two regions. In this investigation we will primarily be concerned with modelling losses that are the loss of conduction a typical house in SA [4]. In addition, for heating/cooling losses, we need to consider how heating is generated in buildings to replenish the lost. Particular sources of interest included the buildings' heating system and the effect of sunlight as well as the effect of the buildings' occupants and the many heat generating devices, which are common inside most Dhahran homes.

4.2 Model Initialization

The initial requirements for modeling thermal house, we need to mean the following components:

- Defines the house geometry (size, number of windows)
- Specifies the thermal properties of house materials
- Calculates the thermal resistance of the house
- Provides the cooler characteristics (temperature of the cooling air, flow-rate)
- Specifies the initial room temperature (20 deg. Celsius = 68 deg. Fahrenheit)

The main model components for the general air conditioning system will explain in the following points:

- **Set Point:**

Set Point or the desired temperature point is a constant block. It specifies the temperature that must be maintained indoors. It is 70 degrees Fahrenheit by default. Temperatures are given in Fahrenheit, but then are converted to Celsius to perform the calculations.

- **Cooler*:***

Cooler is a subsystem that has a constant air flow rate, "$\dot{M}$". The thermostat signal turns the cooler on or off. When the cooler is on, it absorbs hot air at temperature T_{HVAC} (for example 10 degrees Celsius = 50 degrees Fahrenheit by default) at a constant flow rate of $\dot{M}$ (for example 1kg/sec = 3600kg/hr by default). The cool airflow into the house is expressed by the equation 4.1.

$$\frac{dQ_{cooler}}{dt} = (T_{HVAC} - T_{house}) \times \dot{M}_{HVAC} \times C_p \qquad (4.1)$$

- **House model:**

This part deals with model of a house heating system and its developing. The house heating system passes through many stages. The first order, second order model and developed or upgraded house heat models are presented in the next sections. The model developed is based on formulations for the first and second order house heat models. The solution of the problem formulation is obtained using a second order transformation technique.

4.3 House Thermal Model

4.3.1 First order House Heating Model

House is a subsystem that calculates room temperature variations. It takes into consideration the heat flow from the heater and heat losses to the environment. Heat losses derivative are expressed by equation 4.2.

$$\left(\frac{dQ}{dt}\right)_{losses} = \frac{T_{outdoor} - T_{indoor}}{R_{eq}} \tag{4.2}$$

For the simplified case, the values of the thermal resistances (R_{in};R_{out}), and one thermal capacity (C), for the first-order lumped parameter model of the construction element, as it sees in figure 4.1, the main dynamic first-order equation is calculated and represented in equations 4.3 and 4.4.

$$\frac{dT_{room}}{dt} = \frac{1}{M_{air} \cdot C_p} \times \left(-\frac{dQ_{cooler}}{dt} + \frac{dQ_{losses}}{dt} + Q_{int}\right) \tag{4.3}$$

$$\frac{dT_{room}}{dt} = \frac{1}{M_{air} \cdot C_p} \times \left(-\frac{dQ_{cooler}}{dt} + \frac{T_{outdoor} - T_{room}}{R_{eq}} + Q_{int}\right) \quad (4.4)$$

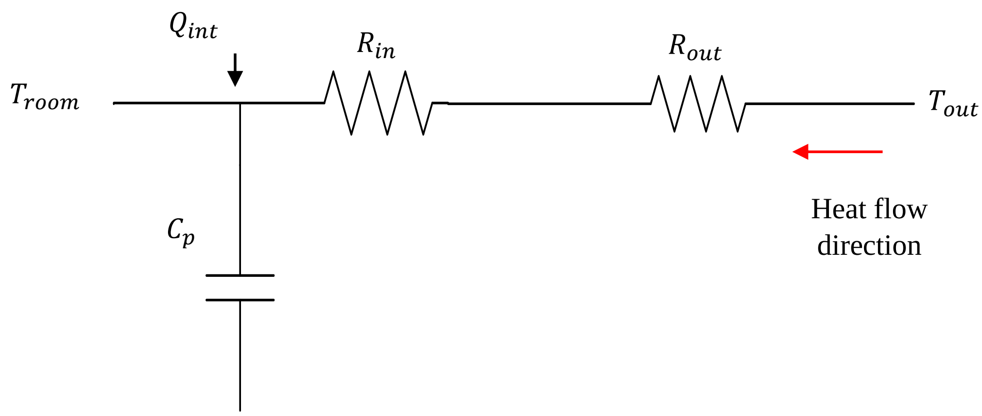


Figure 4.1 Thermal Circuit Model of First Order Home Heating System

Where,

$\dot{M}_{HVAC}$: Mass supply airflow kg/s.

M_{air}: Air mass.

C_p: Air specific heat J/kg.k.

R_{eq}: Equivalent house thermal resistance (R_{in}+R_{out}).

Q_{int}: The sum of convective internal load ($Q_{int} = Q_{Heat\ sources}$)

$T_{outdoor}$: Outdoor temperature.

T_{room}: Indoor temperature.

T_{HVAC}: Supply temperature

4.3.2 Second Order House Heating Model

Developed the model components for second order heat system are explain in the following points. The aim of this section shows that the parameters extracted in real-time were a reasonable representation of the building, in that they could be used to control the heating/cooling plant of a real building. This means that at any instant the model would have to represent the thermal aspects of a building in its present condition, thus allowing predictions to be made [5]. The circuit in figure 4.2 is represented by the state equations 4.5 and 4.6.

$$C_a \frac{dT_i}{dt} = k_l(T_w - T_i) + k_i(T_o - T_i) + q \tag{4.5}$$

$$C_w \frac{dT_w}{dt} = k_l(T_i - T_w) + k_o(T_o - T_w) \tag{4.6}$$

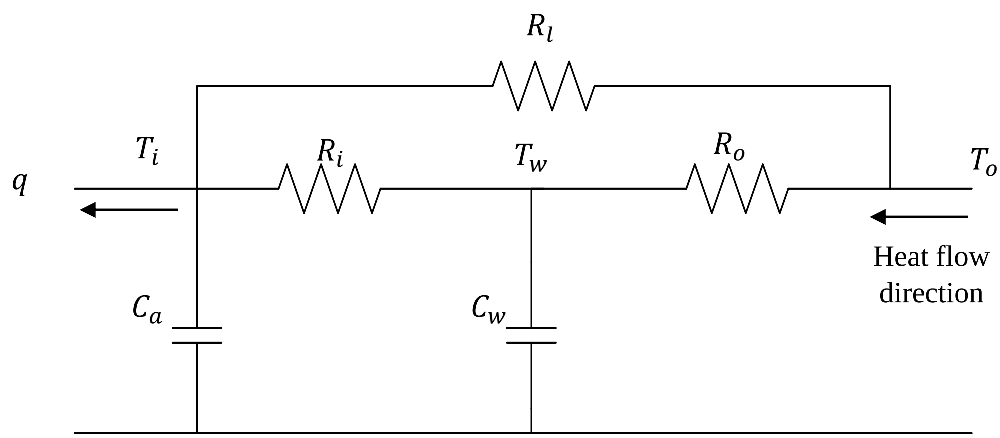


Figure 4.2: Representation of Thermal Response Model Used

Where k_l, k_o and k_i are the inverses of the resistances R_l, R_o and R_i, respectively. R_l, represents the rapid response thermal resistance between the inside temperature node T_i and the outside T_o. R_i, is the inside-to-structure resistance and R_o is the structure-to-outside resistance, C_a, the effective thermal mass of the air, C_w, the effective structural thermal mass. q, is the sum of the heat inputs to the interior; one of these inputs (that from the heating plant) is controllable.

$$Q_m = k_o(T_o - T_w) \tag{4.7}$$

Based on the modified figure 4.3 and the equations 4.1, 4.2, 4.3 and 4.4, the main dynamic second order equations are written and represented in equations 4.8 and 4.9.

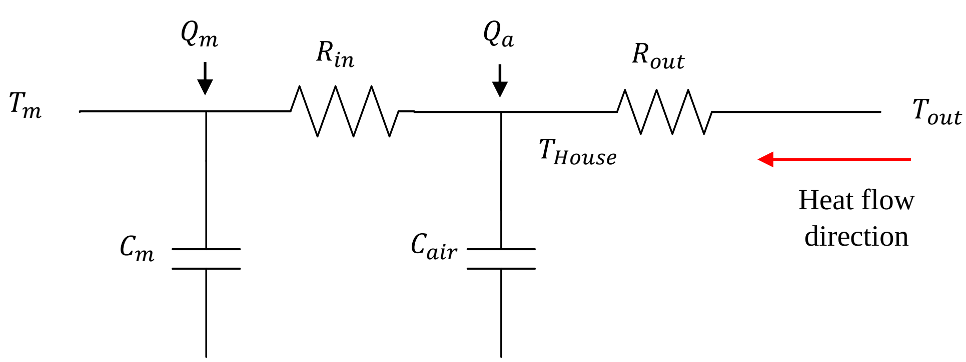


Figure 4.3 Thermal Circuit Model of the Second Order Home Heating System

$$\dot{T}_{House}(t) = \frac{1}{C_a}(U_m \cdot T_{mass}(t) - (U_a + U_m) \cdot T_{House}(t) + Q_a + U_a \cdot T_o(t)\ ) \tag{4.8}$$

$$\dot{T}_{mass}(t) = \frac{1}{C_m}(U_m(T_{air}(t) - T_{mass}(t)) + Q_m) \tag{4.9}$$

Where,

T_{House}: The indoor temperature.

T_{mass}: The inner mass temperature.

T_{out}: The outdoor temperature.

C_a: The thermal mass of the air.

C_m: The thermal mass of the building and furniture.

U_a: The conductive of the building envelope ($U_a = 1/R_{out}$).

U_m: The conductance between the inner air and inner solid mass ($U_m = 1/R_{in}$).

Q_a: The heat flux consists of three gain factors (internal heat gain, solar heat gain and heating/cooling gain) $Q_a = Q_{in} + Q_{so} - Q_c$., Q_m: Mass supply airflow rate

4.3.3 Upgraded Second Order House Heating Model

The upgraded heat model of a house is explained in figure 4.4. Upgraded model components for second order heat system are explained in the following figures. The aim of this section shows the parameters extracted in real-time were a reasonable representation of the building, in that they could be used to control the cooling plant of a real building. This means that at any instant the model would have to represent the thermal aspects of a building in its present condition, thus allowing predictions to be made.

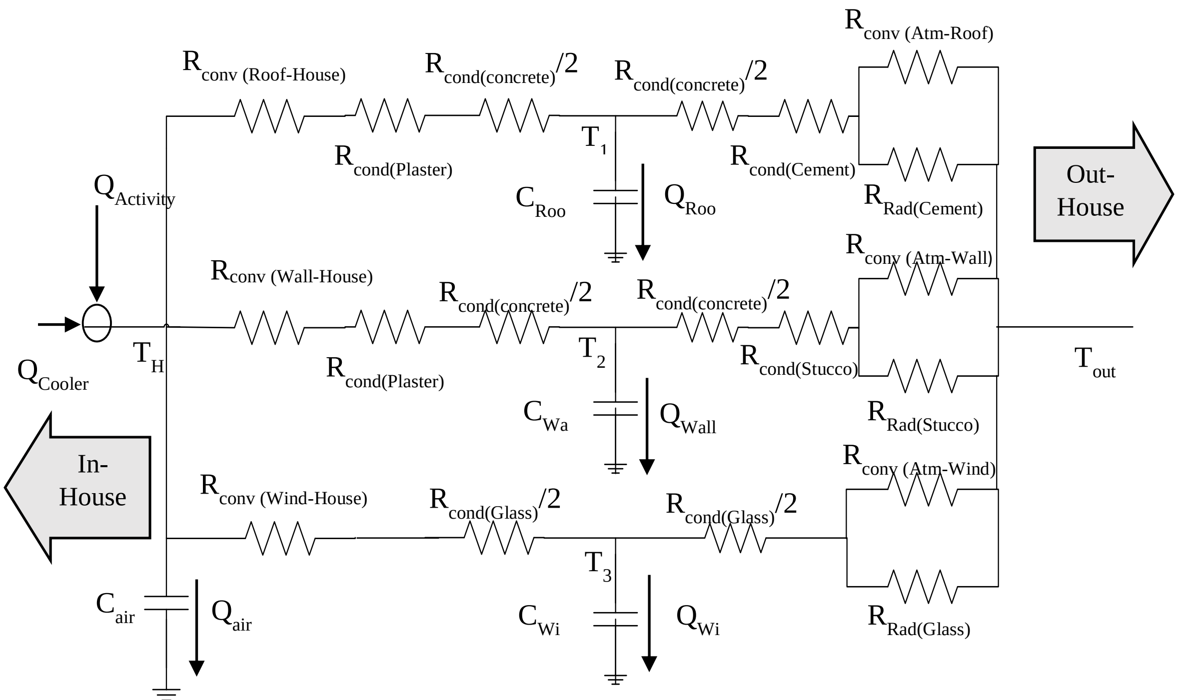


Figure 4.4: Thermal Circuit Model of the Upgraded Home Heating System

The model is reduced in figure 4.5 by collecting $R_{11}, R_{12}, R_{21}, R_{22}, R_{31}\ and\ R_{32}$

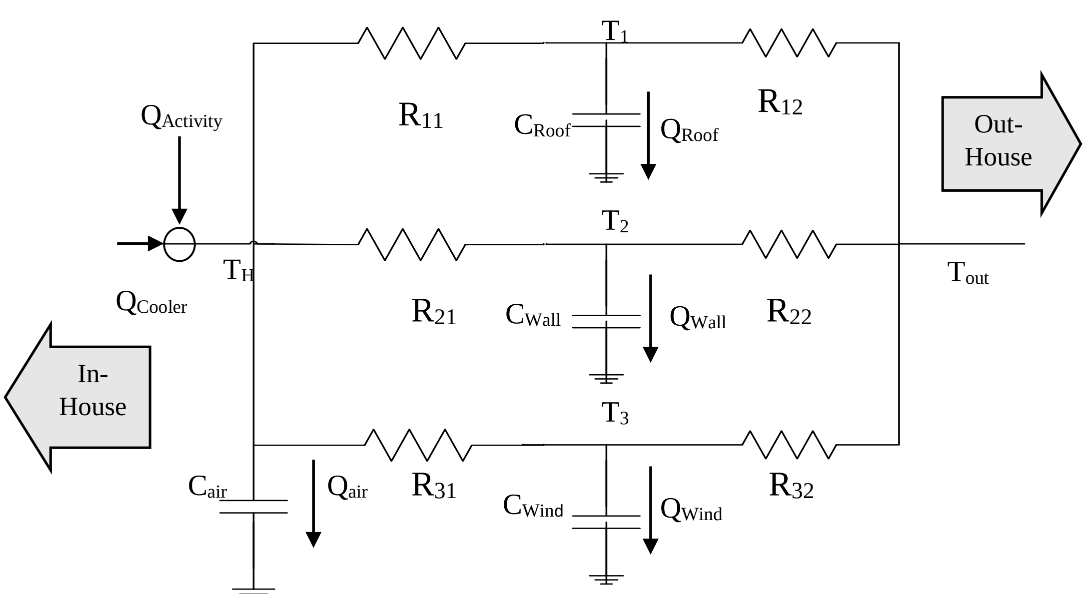


Figure 4.5: Reduced Thermal Circuit Model of the Upgraded Home Heating System

The convective, conductive and radiative resistance values are offered by the following equations:

$$R_{Convective} = \frac{1}{H_{Conv} * A} \qquad °C/W \tag{4.10}$$

$$R_{Conductive} = \frac{l}{k_{Cond} * A} \qquad °C/W \tag{4.11}$$

$$R_{Radiative} = \frac{1}{h_{rad} * A} \qquad °C/W \tag{4.12}$$

The equivalent resistances for figure 4.5 are presented by R_{11}, R_{12}, R_{21}, R_{22}, R_{31}, and R_{32}

$$R_{11} = R_{conv(Roof-House)} + R_{cond(plaster)} + \frac{R_{cond(concrete)}}{2} \tag{4.13}$$

$$R_{12} = \frac{R_{cond(concrete)}}{2} + R_{cond(cement)} + R_{conv(Roof-Atm)} /\!/ R_{Rad(cement)} \tag{4.14}$$

$$R_{21} = R_{conv(Wall-House)} + R_{cond(plaster)} + \frac{R_{cond(concrete)}}{2} \tag{4.15}$$

$$R_{22} = \frac{R_{cond(concrete)}}{2} + R_{cond(stucco)} + R_{conv(Atm-Wall)} /\!/ R_{Rad(stucco)} \tag{4.16}$$

$$R_{31} = R_{conv(Wind-House)} + \frac{R_{cond(Glass)}}{2} \tag{4.17}$$

$$R_{32} = \frac{R_{cond(Glass)}}{2} + R_{conv(Atom-Glass)} /\!/ R_{Rad(Glass)} \tag{4.18}$$

Where, the conductance or U values equal to the invers of equivalent resistances:

$$U_{11} = \frac{1}{R_{11}} \quad , \quad U_{12} = \frac{1}{R_{12}}$$

$$U_{21} = \frac{1}{R_{21}} \quad , \quad U_{22} = \frac{1}{R_{22}}$$

$$U_{31} = \frac{1}{R_{31}} \quad , \quad U_{32} = \frac{1}{R_{32}}$$

Based on the modified figure 4.5, the absorbed heat in house air, floor, wall and windows are represented as thermal dynamic equations and we can rewrite these equations and represent them in following equations:

$$Q_{\substack{absorbed\ in \\ the\ House\ Air}}(t) = \frac{dT_H}{dt} * C_{Air} \tag{4.19}$$

$$Q_{\substack{absorbed \\ in\ the\ Roof}}(t) = \frac{dT_1}{dt} * C_{Roof} \tag{4.20}$$

$$Q_{\substack{absorbed \\ in\ the\ Walls}}(t) = \frac{dT_2}{dt} * C_{Wall} \tag{4.21}$$

$$Q_{\substack{absorbed \\ in\ the\ Winds}}(t) = \frac{dT_3}{dt} * C_{Wind} \tag{4.22}$$

$$Q_{\substack{absorbed\ in \\ the\ House\ Air}}(t) = Q_{\substack{Heat\ passes \\ to\ house}}(t) + Q_{\substack{Heat\ Sources \\ in\ House}}(t) - Q_{Cooler} - \left(Q_{\substack{absorbed \\ in\ the\ Roof}} + Q_{\substack{absorbed \\ in\ the\ Walls}} + Q_{\substack{absorbed \\ in\ the\ Winds}} \right) \tag{4.23}$$

According to the equations 4.19, 4.20, 4.21 and 4.22, the passing heat through roof, walls and windows and the absorbed heat in roof, wall and windows are explained in the following equations:

$$Q_{\substack{Heat\ passes \\ to\ the\ house}}(t) = Q_{\substack{Heat\ passes \\ through\ Roof}}(t) + Q_{\substack{Heat\ passes \\ through\ Wall}}(t) + Q_{\substack{Heat\ passes \\ through\ Winds}}(t) \quad (4.24)$$

$$Q_{\substack{Heat\ passes \\ through\ Roof}}(t) = Q_{\substack{absorbed \\ in\ the\ Roof}} + U_{11}\big(T_1(t) - T_H(t)\big) \quad (4.25)$$

$$Q_{\substack{Heat\ passes \\ through\ Wall}}(t) = Q_{\substack{absorbed \\ in\ the\ Walls}} + U_{21}\big(T_2(t) - T_H(t)\big) \quad (4.26)$$

$$Q_{\substack{Heat\ passes \\ through\ Winds}}(t) = Q_{\substack{absorbed \\ in\ the\ Winds}} + U_{31}\big(T_3(t) - T_H(t)\big) \quad (4.27)$$

Back to the previous equations (4.19 to 4.22) and the equations (4.25 to 4.27), the following equations are presented the thermodynamic working for the house parameters:

$$Q_{\substack{absorbed\ in \\ the\ House\ Air}}(t) = U_{11}\big(T_1(t) - T_H(t)\big) + U_{21}\big(T_2(t) - T_H(t)\big) +$$
$$U_{31}\big(T_3(t) - T_H(t)\big) + Q_{\substack{Heat\ Sources \\ in\ House}}(t) - Q_{Cooler} \quad (4.28)$$

$$\dot{T}_H(t) = \frac{1}{C_{Air}}\Big(U_{11} \cdot T_1(t) + U_{21} \cdot T_2(t) + U_{31} \cdot T_3(t) - T_H(t)(U_{11} + U_{21} + U_{31}) +$$
$$Q_{\substack{Heat\ Sources \\ in\ House}}(t) - Q_{Cooler}\Big) \quad (4.29)$$

$$\dot{T}_1(t) = \frac{1}{C_{Roof}}\Big(U_{12}\big(T_{out}(t) - T_1(t)\big) - U_{11}\big(T_1(t) - T_H(t)\big)\Big) \tag{4.30}$$

$$\dot{T}_2(t) = \frac{1}{C_{Wall}}\Big(U_{22}\big(T_{out}(t) - T_2(t)\big) - U_{21}\big(T_2(t) - T_H(t)\big)\Big) \tag{4.31}$$

$$\dot{T}_3(t) = \frac{1}{C_{Window}}\Big(U_{32}\big(T_{out}(t) - T_3(t)\big) - U_{31}\big(T_3(t) - T_H(t)\big)\Big) \tag{4.32}$$

Where,

A: Area

H: Heat transfer coefficient

k: Thermal conductivity

h: Radiation coefficient

l: Thickness.

T_out: External house temperature. ℃

T_H: Internal house temperature. ℃

T_1: Internal roof temperature. ℃

T_2: Internal wall temperature. ℃

T_3: Internal windows temperature. ℃ C_Air: Specific heat of air and it equals to M_Air (Mass of air inside the house)+ c (heat capacity of air) J/℃

C_Roof: Specific heat of roof and it equals to M_Air (Mass of roof)+c (heat capacity of roof). J/℃

C_Wall: Specific heat of wall and it equals to M_Air (Mass of wall) +c (heat capacity of wall). J/℃

C_Wind: Specific heat of window and it equals to M_Air (Mass of wind) +c (heat capacity of wind) J/℃

Q_Air:The energy stored in the space area of house. J/s

Q_Wall:The heat energy stored in the wall. J/s

Q_Roof:The heat energy stored in the roof. J/s

Q_Wind:The heat energy store in the windows. J/s

Q_(Heat house Sources):The heat energy supplied from activity human and furniture in the space area of house. J/s

4.4 House Thermal Model Using Simscape Physical System

4.4.1 Simscape Physical System Modeling

With Simscape, we build a model of a system just as you would assemble a physical system. Simscape employs a physical network approach, also referred to as a causal modeling, to model building: Components (blocks) corresponding to physical elements, such as pumps, motors, and op-amps, are joined by lines corresponding to the physical connections that transmit power. This approach lets us describe the physical structure of a system rather than the underlying mathematics. From our model, which closely resembles a schematic, Simscape automatically constructs the differential algebraic equations (DAEs) that characterize the system's behavior. These equations are integrated with the rest of the Simulink model, and the DAEs are solved directly. The variables for the components in the different physical domains are solved simultaneously, avoiding problems with algebraic loops.

Simscape lets us create models of custom components by using the basic elements contained in its foundation libraries. Figure 4.6 shows the Simscape libraries of electrical, mechanical, hydraulic, and thermal building blocks for creating customized component models. Therefore, we will discuss two main types, which are used in our thesis of the physical modeling components.

Modeling Electrical Components: Simscape provides electrical building blocks for representing electrical components and circuits. In addition to basic elements like resistors, capacitors, and inductors, more complex elements such as op-amps and transformers are also included. More elaborate electronic and electromechanical components are available in SimElectronics™.

Modeling Thermal Effects: Simscape provides thermal building blocks for modeling and simulating thermal effects in your system. We can model conductive, convective, and radiative heat transfer as well as the thermal mass of elements. Using thermal source blocks, you can specify the temperature or heat transfer; using thermal sensor blocks, you can measure the amount of heat transfer or temperature change.

4.4.2 Working with Simscape Physical Signals

With Simscape our models can include physical signals that have units associated with them. We specify the units and parameter values in the block dialog boxes, and Simscape performs the necessary unit-conversion operations when solving a physical network. The Physical Signals block library lets you perform math operations on physical signals and graphically enter equations inside the physical network. Physical signal ports are used in Simscape block diagrams to better integrate physical signals into our physical system, which increases computational speed.

Using the elements contained in these foundation libraries, we can create more complex components with different physical domains. As with Simulink, we can then group this assembly of blocks into a subsystem and parameterize it to reuse and share these components.

Simscape sensor blocks are displayed in figure 4.6 which use to measure values for different physical quantities such as thermal (flow rate, temperatures) and then pass these signals into standard Simulink blocks. Source blocks enable Simulink signals to assign values to any of these variables. Sensor and source blocks let us connect a control algorithm developed in Simulink to a Simscape network.

4.4.3 Building the House Thermal Model using Simscape Physical System

Now let us build a Simscape model. We will need the following components:

1. a model of the thermal mass,
2. a model of the convective, condictive and radative resistances,
3. a reference temperature,
4. a source temperature to specify intial temperatures T_1, T_2 & T_3
5. a way to measure the house temperatures at the steady state T_{House} T_1, T_2 & T_3. and
6. a way to measure the absorbed heat in air house and the house heat flow through roof, walls and windows.

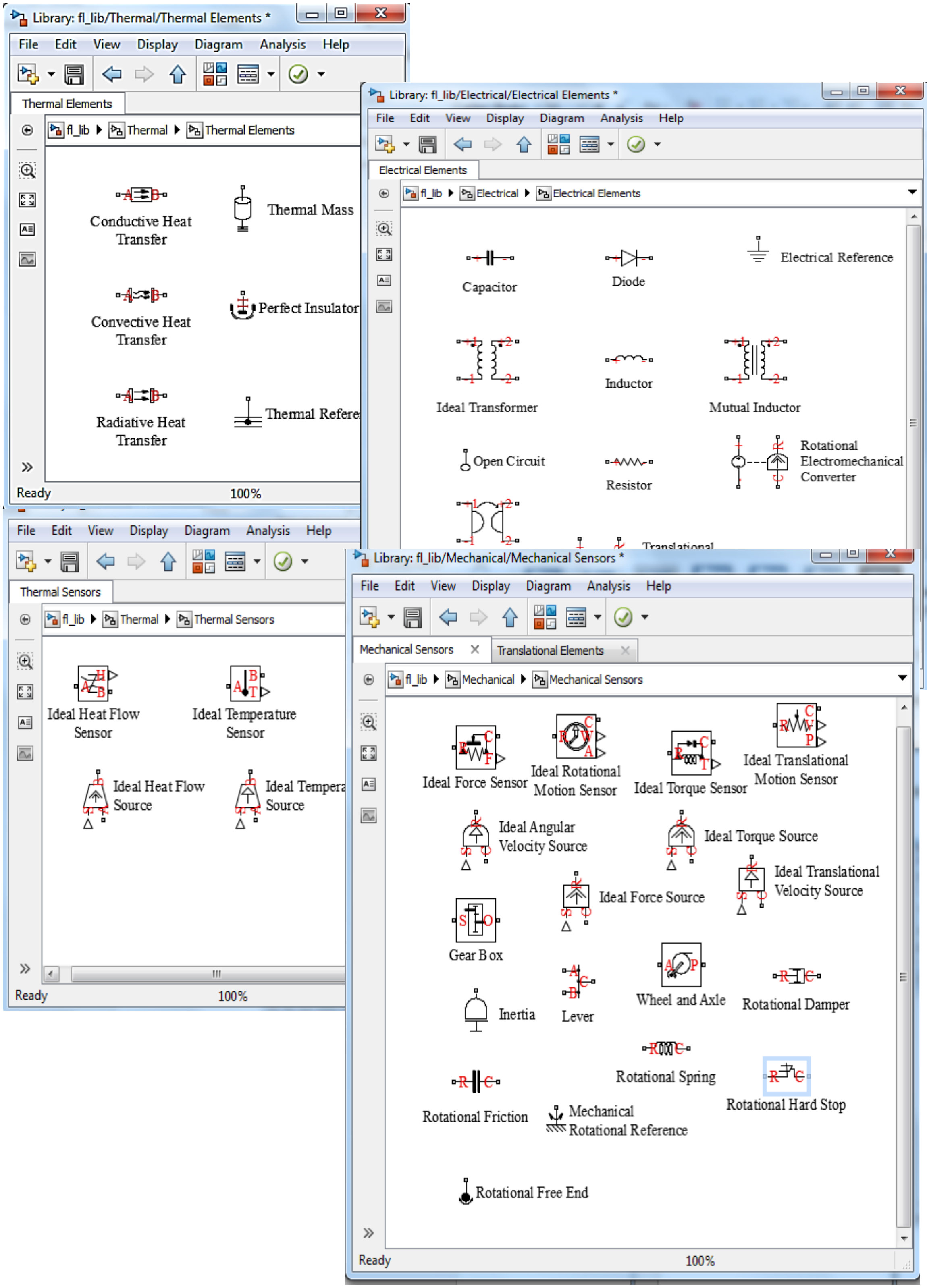


Figure 4.6 Simscape Libraries of Electrical, Mechanical, Hydraulic and Thermal Building Blocks for Creating Customized Component Models.

A cooling house model is displayed in figure 4.7 that consist of a cooler, thermostat, and a house structure with four thermally distinguishable parts: inside air, house walls, windows, and roof. The house exchanges heat with the environment through its walls, windows, and roof. Each path is simulated as a combination of a thermal convection, thermal conduction, and the thermal mass.

The physical roof model is presented in figure 4.8. The roof consists of three layers plaster from inside, concrete and boxes of squares cement on outside roof. Therefore, plaster, concrete and squares cement layers have conductive thermal module. Plaster and cement layers have convective module. Out side cement layer also has radiative module. Thermal mass is added in the mid-thickness for roof weight which reflects the ability of a combination layers of roof materials to store internal energy.

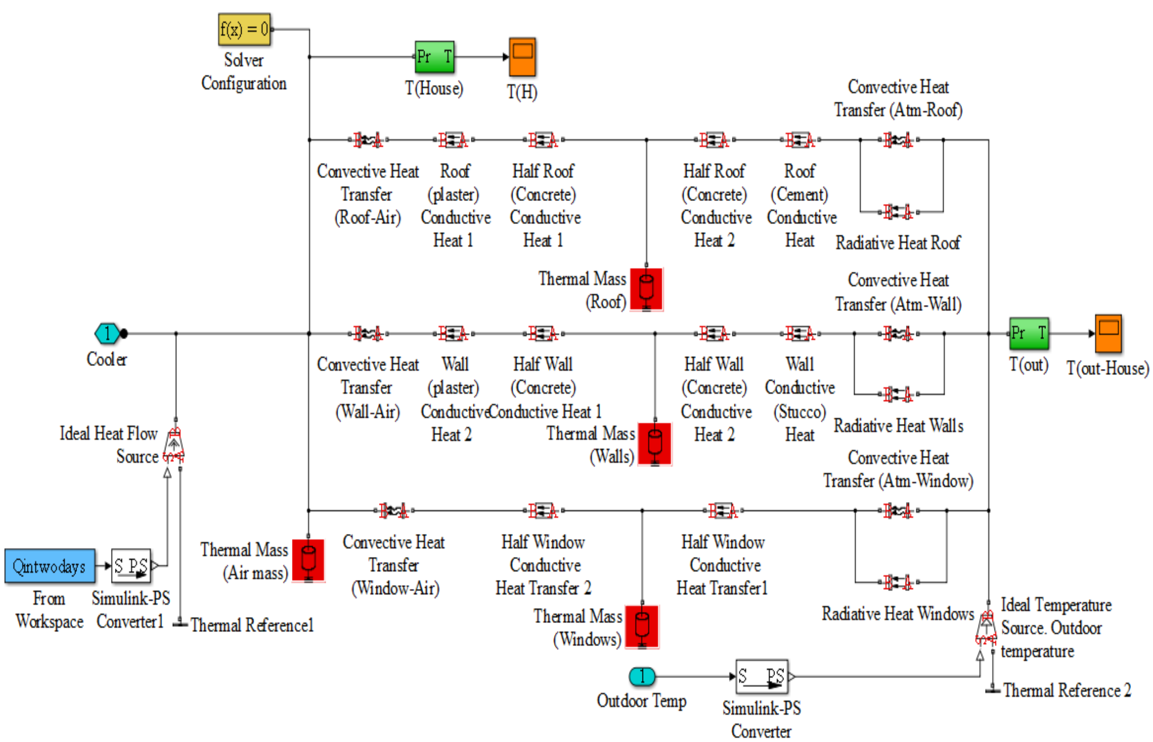


Figure 4.7: House Thermal Model Using Physical System

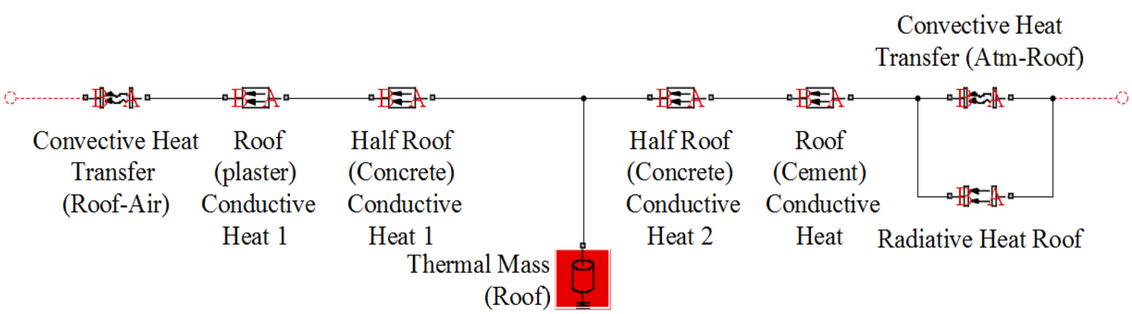


Figure 4.8: House Roof Thermal Model Using Simscape Physical System

Similarly the physical walls model is presentd in figure 4.9. The wall consists of three layers plaster from inside, concrete and stucco on outside. Therefore, plaster, concrete and stucco layers have conductive thermal module. Plaster and stucco layers have convective module. Out side stucco layer also has radiative module. Thermal mass is added in the mid-thickness for overall walls weight which reflects the ability of a combination layers of wall materials to store internal energy.

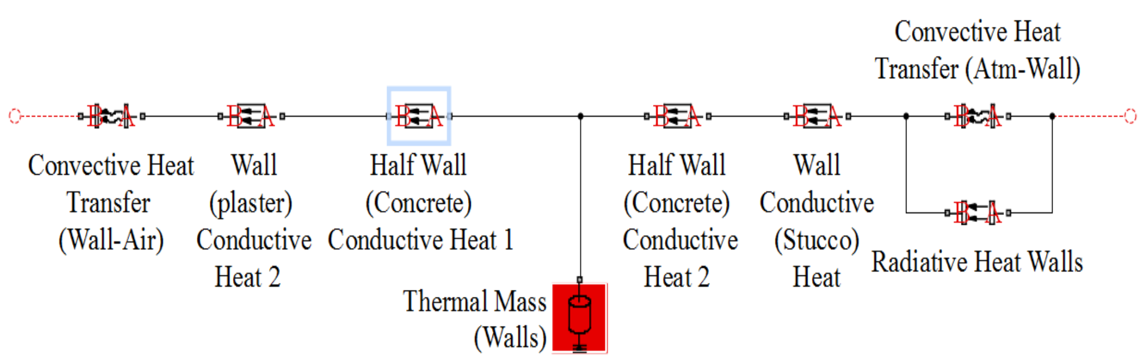


Figure 4.9 House Walls Thermal Model Using Physical System

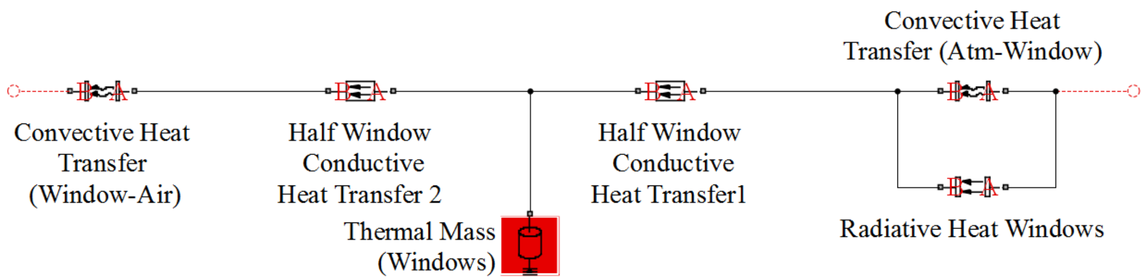


Figure 4.10 House Windows Thermal Model Using Physical System

The windows consist only of one glass layer which are explained in figure 4.10. Therefore, they have conductive thermal model for glass thickness and convective model for inside house. They also have convective and radiative models for outside house. Thermal mass is added in the mid-thickness for overall windows weight which reflects the ability of a combination layers of wall materials to store internal energy.

The Simulink-PS (S-PS) Converter blocks in figure 4.11 are used to convert the input Simulink signal into a physical signal. We use these blocks to connect Simulink sources (heat flow or temperatures) to the inputs of a Physical Network diagram. The Ideal Heat Flow Source block in figure 4.11.a & b represents an ideal source of thermal energy that is powerful enough to maintain specified heat flow at its outlet regardless of the temperature difference across the source. Figure 4.11.c shows the Ideal Temperature Source block, which represents an ideal source of thermal energy that is powerful enough to maintain specified temperature at its outlet regardless of the heat flow consumed by the system.

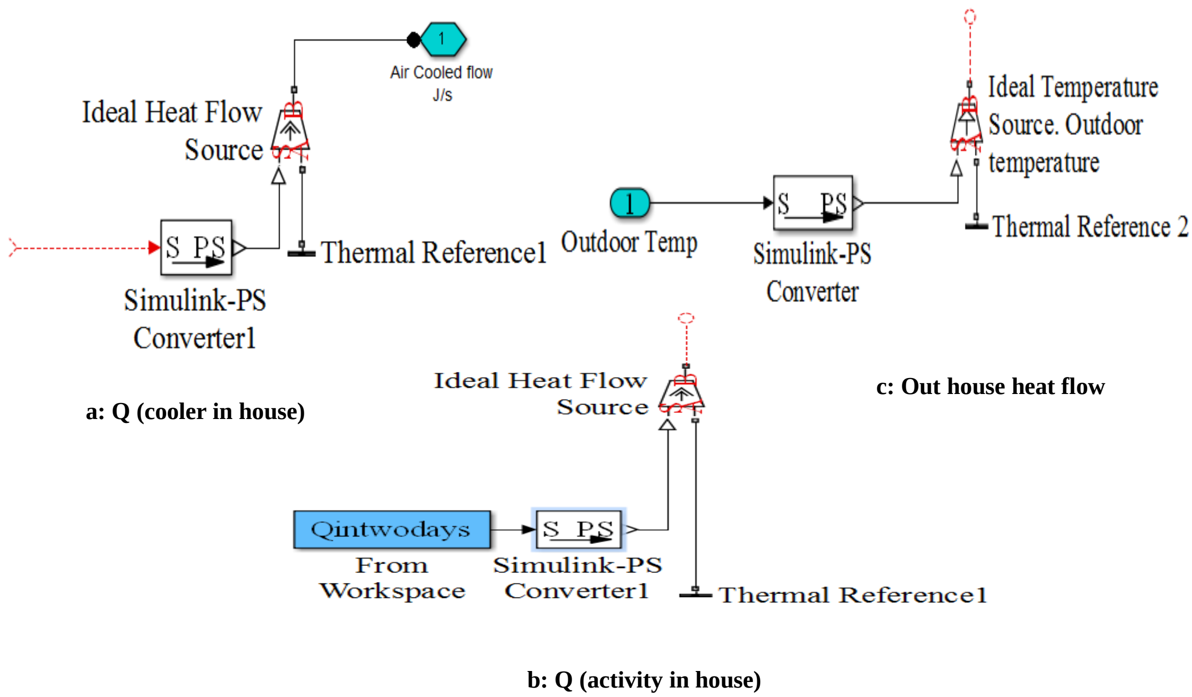


Figure 4.11 Block Diagrams for Convert Untitled Signal to Simscape Physical Signal

4.5 Heat Model of HVAC ON/OFF Cycle

Figure 4.12 displayed the desired temperature (Setting Point Temperature) that is compared with the house temperature (T_{House}) and then it gives temperature error (T_{err}). The error is compared with the fluctuation value of thermostat relay. If T_{err} is above the fluctuation value, the relay is turned on and if T_{err} is below the fluctuation value, the thermostat relay is turned off. The cooling air flow and outdoor temperature (T_{out}) is considered in the thermodynamic model for the house and T_{House} , mid parameters temperature such as roof, walls and windows are output. And so on, the house temperature (T_{House}) is compared with thermostat setpoint.

Figure 4.12 also shows the block diagram of integrate ON/OFF cycle air conditioning system with thermal house models respectively based on the thermal dynamic equations (4.1 - 4.4), (4.8 - 4.9) and (4.29 - 4.32).

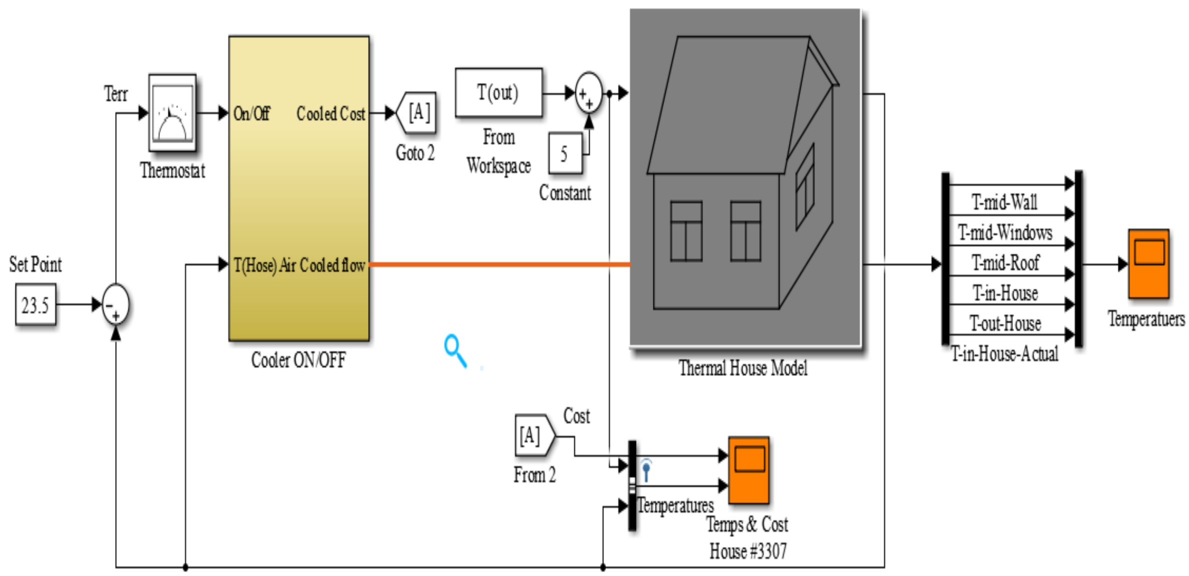


Figure 4.12 Integrate ON/OFF Cycle A/C System with Thermal House Models

The block diagram of the cooler subsystem is displayed in figure 4.13 that is for both first order and second order thermal house models based on the thermal dynamic equation 4.1.

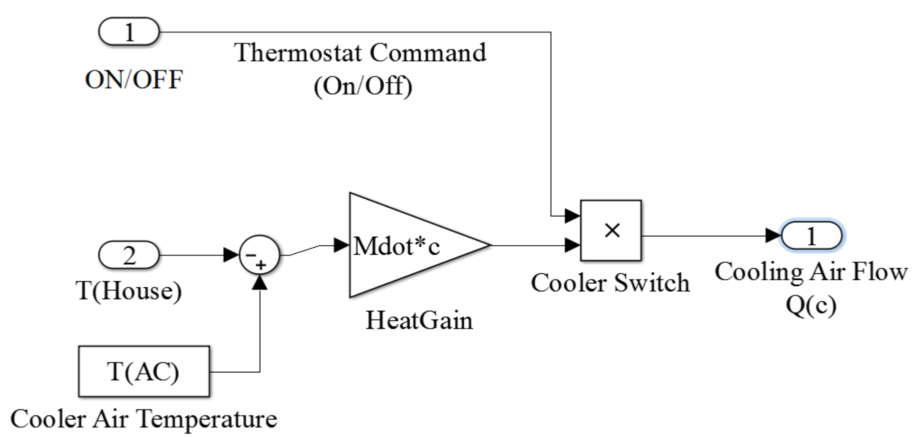


Figure 4.13 Cooler Subsystem on ON/OFF Cycle System

The ON/OFF signal is coming from the thermostat relay. The cooling airflow (Q_c) into the house produced from the difference value between indoor temperature (T_{House}) and cooler air temperature ($T_{A/C}$) and then multiplied by cooling gain.

Figure 4.14 shows the block diagram of the first order house model subsystem based on the thermal dynamic equation 4.4. The inputs of the first order thermodynamic model of house are the internal load produced by convection, the cooling airflow and the cooling losses, which are produced from difference between indoor and outdoor temperature. The output of the house thermal model is indoor temperature T_{indoor} .

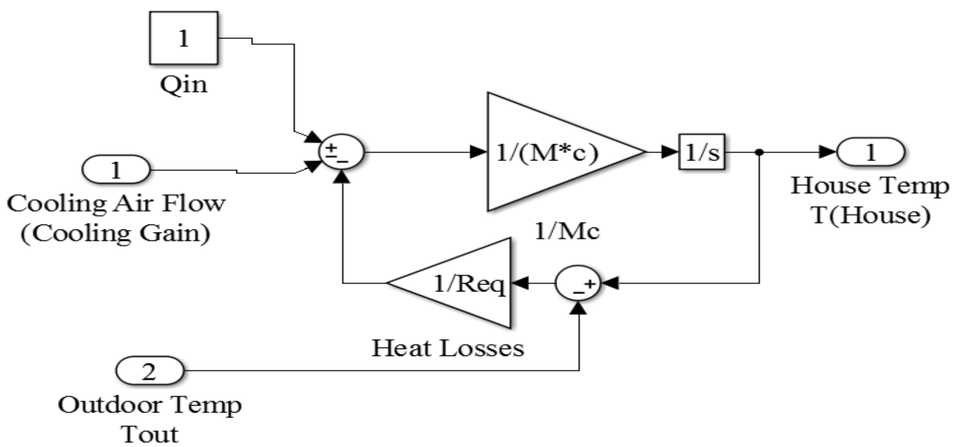


Figure 4.14 First Order Thermodynamic Model of the House

The block diagram of the second order thermal house model subsystem is presented in figure 4.15 based on the thermal dynamic equations 4.8 and 4.9. The indoor air temperature T_{House} and the inner mass temperature (T_{mass}) will be evaluated from the contribution of sex signals the mass supply airflow rate, the cooling gain, the solar heat gain, internal heat gain, the cooling losses of the conductance of the building envelope and the conductance between the inner air and inner solid mass.

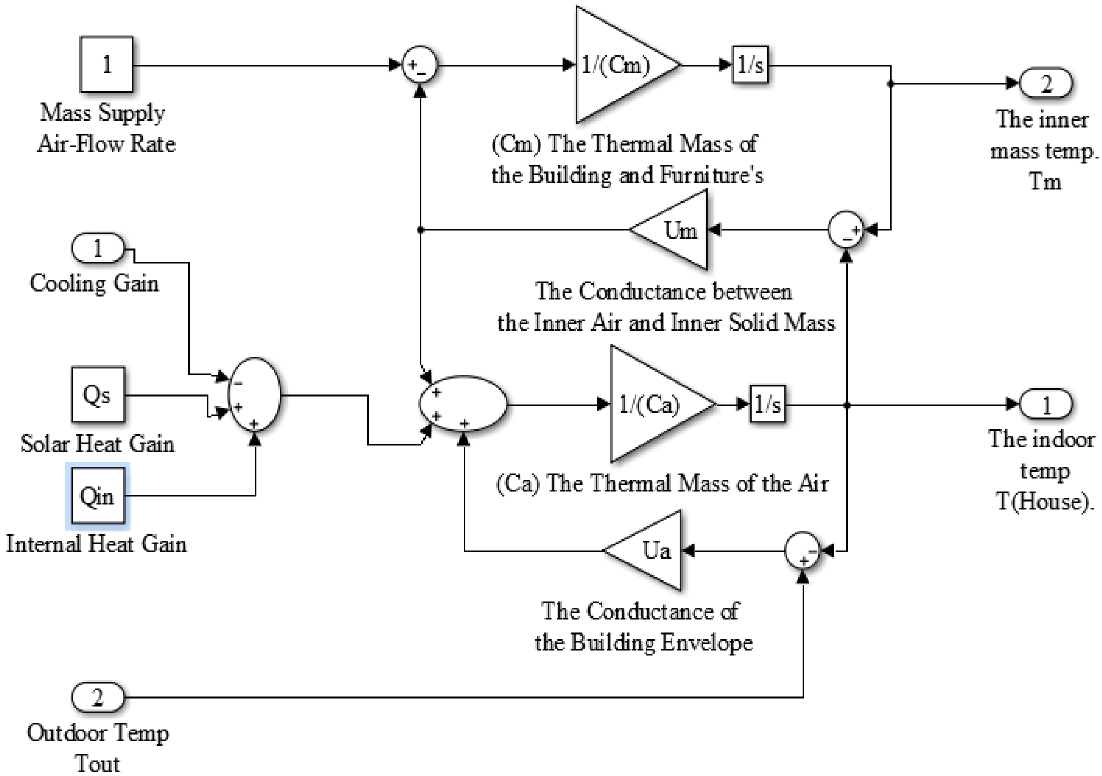


Figure 4.15 Second Order Thermodynamic Model of the House

The block diagram of the upgraded thermal house model subsystem is displayed in figure 4.16 based on the thermal dynamic equations 4.29, 4.30, 4.31 and 4.32. The in-house air temperature T_{House}, roof, wall and roof temperatures (T_1, T_2 & T_3) are evaluated from the contribution of five signals (cooling gain, house heat sources (the solar heat gain and the internal heat gain), cooling losses of the conductance building envelope and the conductance between the in-house air and the mid thickness of roof, walls and windows with ambient air).

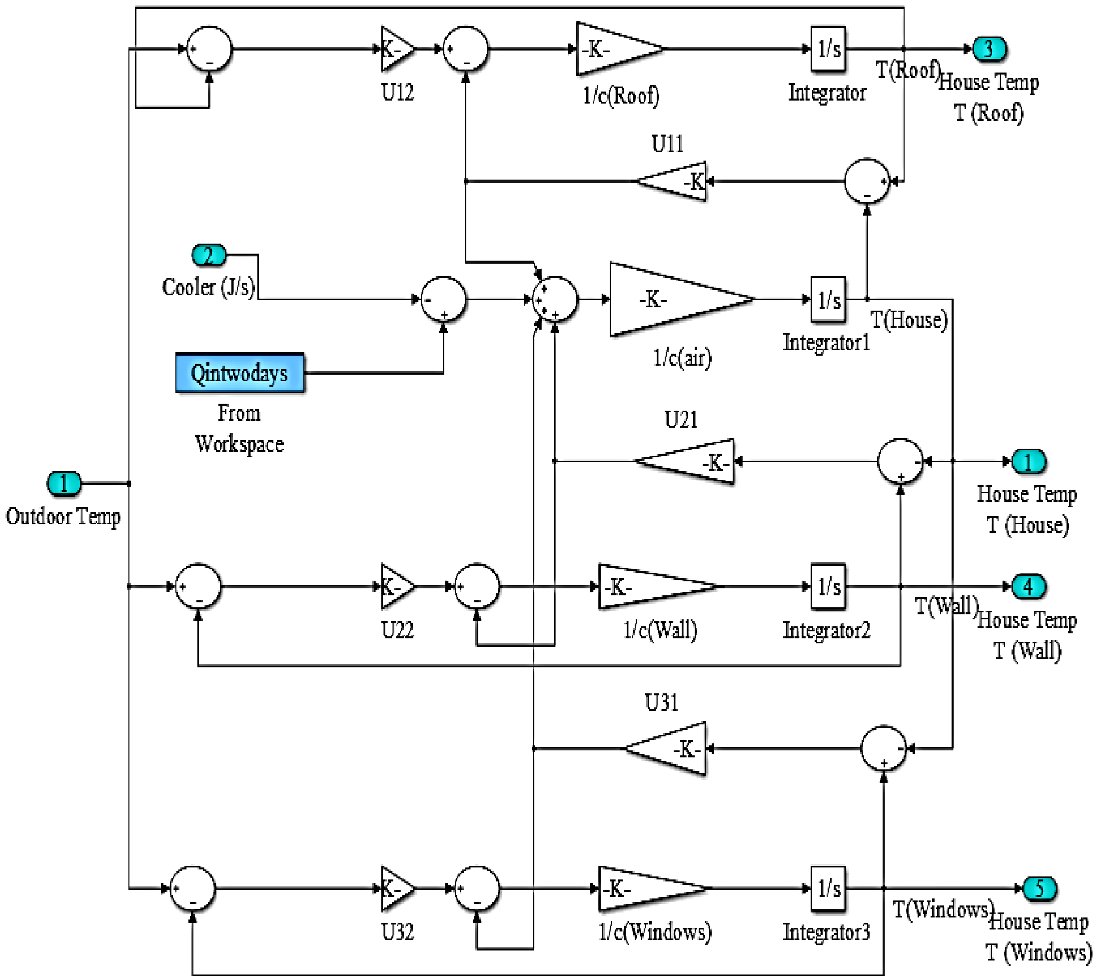


Figure 4.16 The Upgraded Thermodynamic Model of the House

4.5.1 House Thermal Model Using Simscape Physical System

The Simulink in figure 4.17 shows how to model a house cooling system that consist of a cooler, thermostat, and a house structure with four thermally distinguishable parts: inside air, house walls, windows, and roof. A cooler, thermostat, and house structure systems are explained in figures 4.18, 4.19 and 4.20 respectively. The house exchanges heat with the environment through its walls, windows, and roof. Each path simulated as a combination of a thermal convection, thermal conduction, and the thermal mass. The cooler starts absorbed hot air if room temperature exceed the desired temperature and is turned OFF, if temperature falls down desired temperature. As a result, we can monitor the temperatures of house parts and heat losses through them.

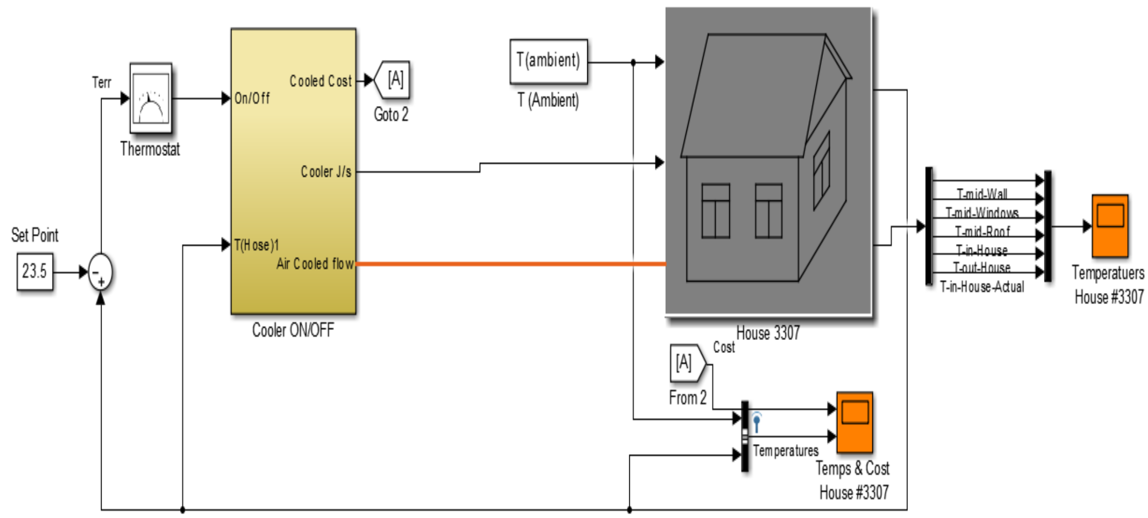


Figure 4.17 Complete House Thermal Model of ON/OFF Technology Using Simscape Physical System

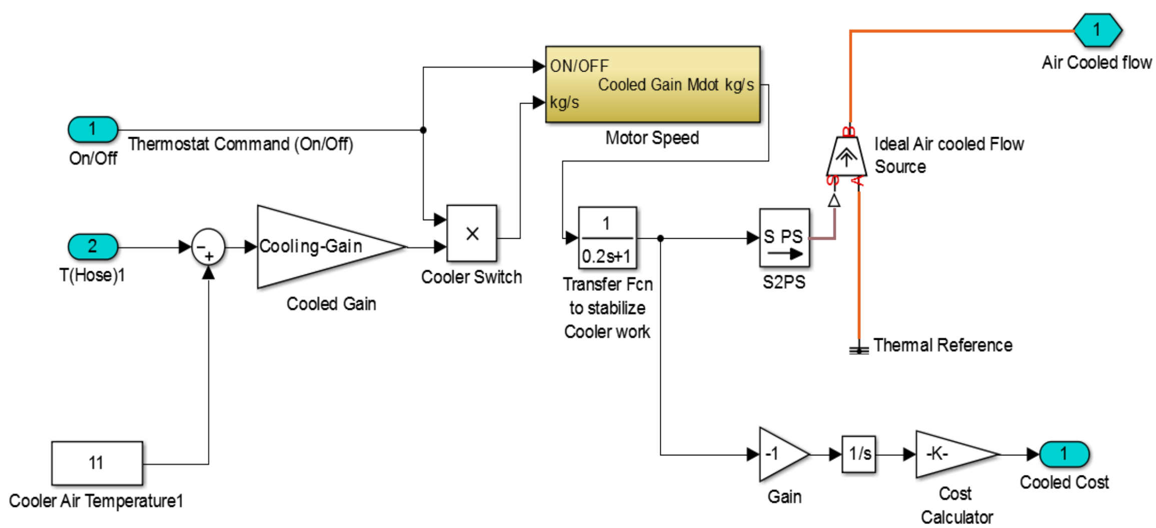


Figure 4.18: Cooler Subsystem Model on ON/OFF Cycle System

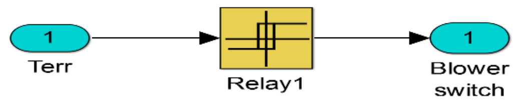


Figure 4.19 Thermostat Subsystem Model

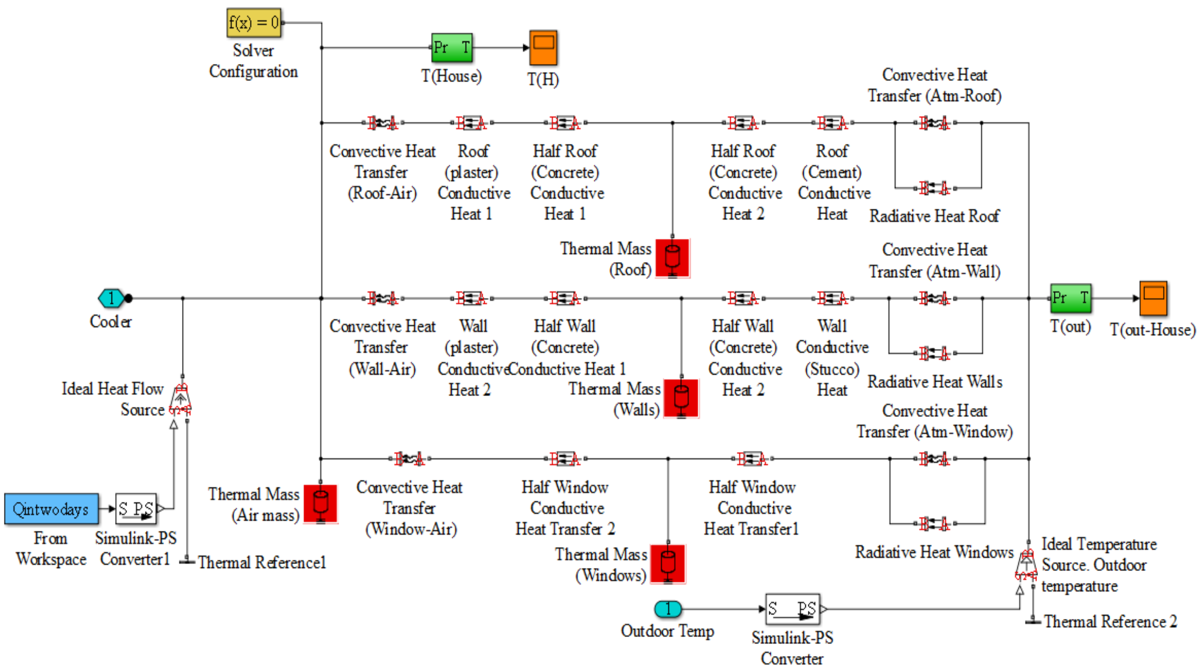


Figure 4.20 Complete House Thermal Model Using Simscape Physical Components

4.6 Heat Model of HVAC VFD System

Converting the input alternative (AC) voltage to direct (DC) voltage and then back to alternative (AC) voltage is considered the principle operation for VFD. As the speed of an induction motor is proportional to the frequency of the AC, the compressor and the blower of the air conditioning run at different speeds. There are two currently categories used to carry out these operations, the Silicon-Controlled-Rectifiers (SCRs) or the Insulated-Gate-

Bipolar-Transistors (IGBTs). The switching of DC voltage occurs by using IGBTs to produce desirable AC voltage, which sometime is called inverter. The IGBTs generate the AC voltage waveform using pulse-width-modulated (PWM) switching [38].

The desired AC voltage waveform is created by switching ON/OFF IGBTs depending on the in-house temperature that calculates the desired speed/frequency using controller unit “Connected Programmable Controller (c.pCO)” and then deliver producing power to the compressor motor on A/C unit. Figure 4.21 shows the block diagram for variable speed compressor of A/C system.

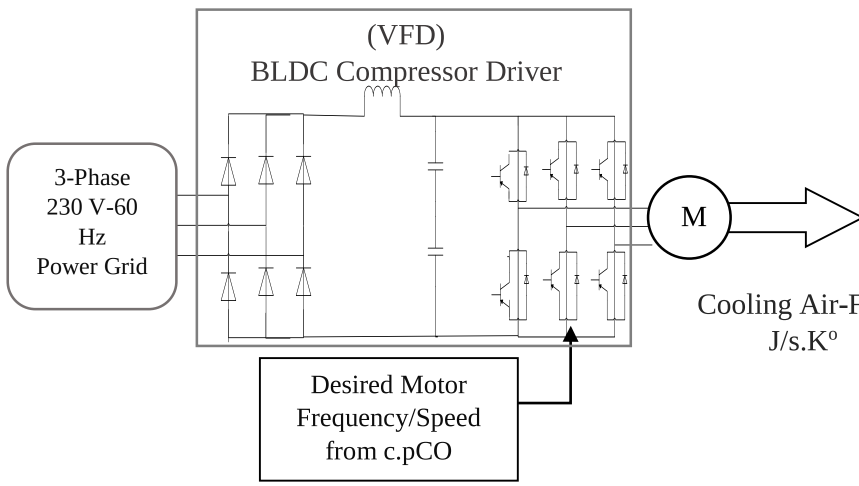


Figure 4.21 Block Diagram for Variable Speed A/C System

The complete block diagram for VFD air–conditioning system with the upgraded thermal house model is displayed in figure 4.22. If the indoor temperature T_{indoor}varies nearby the desired temperature (Set Point), we immediately measure and calculate the desired speed depending on the setting and house temperatures. The desired speed/frequency depends on measuring temperatures like supply air temperature, return air temperature, discharge and suction temperatures, discharge and suction pressure that are detected by c.pCO. the desired value is calculated continuously using c.pCO through proportional-integraland-derivative controller (PID). The input of the VFD is desired speed/frequency (N/ F) that do as a controller to reduce or increase the speed of air conditioning compressor using IGBTs. Cooler gain of air ($Cooler\ Gain \frac{J}{s.K^o}$) is the output of compressor that multiplied by the difference between T_{House} and T_{HVAC} to get appropriate cooling airflow ($\frac{J}{s}$). T_{HVAC} value depends on the electronic expansion valve (ExV) that is controlled using c.pCO through PID. The inputs into thermal house model are the outhouse air temperature and the smooth cooling airflow, and the output is T_{House}.

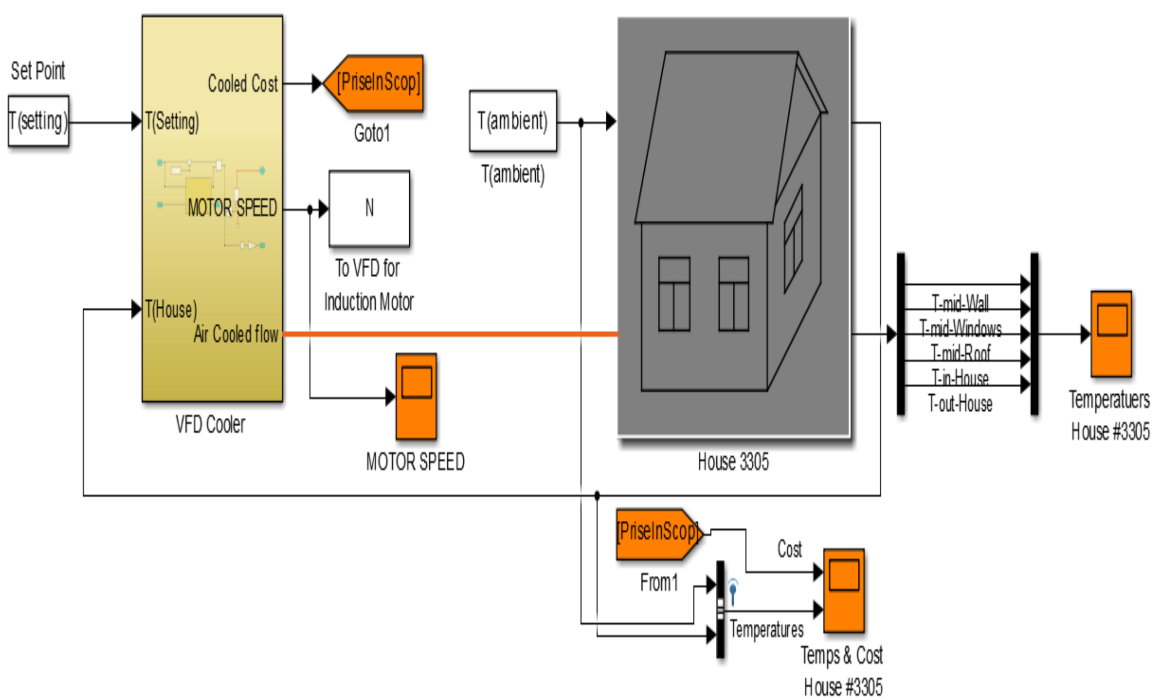


Figure 4.22: Complete House Thermal Model on VFD Technology Using Simscape Physical Components

The Simulink in figure 4.23 shows a house cooling system that consists of a cooler subsystem. Cooler has two options constant value and variable air flow rate, "$\dot{M_{HVAC}}(t)$". Based on the equation 4.33, the variable airflow rate is delivered form cooler system using PI system. The air specific heat is multiplied with airflow rate to produce cooler gain by equation 4.34. The HVAC coil temperature (T_{HVAC}) is variable values that is controlled by PI system. Equation 4.35 is used to calculate the absorbed heat flow from air house.

$$\dot{M_{HVAC}}(t) = K_0 \frac{d\left(T_{Setting} - T_{House}(t)\right)}{dt} + K_1 T_{House}(t) \tag{4.33}$$

$$Cooler\ Gain(t) = \dot{M_{HVAC}}(t) * C_p \tag{4.34}$$

$$T_{HVAC} = K_2 \frac{d\left(T_{Setting} - T_{House}(t)\right)}{dt} + K_3 T_{House}(t) \tag{4.35}$$

$$\frac{dQ_{Cooler}(t)}{dt} = (T_{House} - T_{HVAC}) * \left(Cooler\ Gain(t)\right) \tag{4.36}$$

Where,

$\frac{dQ_{Cooler}(t)}{dt}$: The absorbed heat flow form air house by cooler.

$\dot{M}_{HVAC}(t)$: Mass supply air flow kg/s.

C_p: Air specific heat J/kg.K.

T_{House}: In-House temperature.

T_{HVAC}: HVAC coil A/C temperature.

K_0: The effective cooler gain Kg/K (default $K_0 = 1$ kg/K).

K_1: The effective time cooler gain Kg/s.K (default $K_1 = 1$ kg/s. K).

K_2: The effective HVAC gain (default $K_2 = 0.005$).

K_3: The effective time HVAC gain s^{-1} (default $K_3 = 0.9\ s^{-1}$) .

Figure 4.23 shows the block diagram of the subsystem of cooler for upgraded order thermal house model based on the thermal dynamic equation 4.36. T_{House} and $T_{Setting}$ are the inputs signal for HVAC coil temperature subsystem and cooling air flow subsystem. The cooling airflows (Q_{cooler}) into the house which is produced from the difference value between indoor temperature (T_{House}) and HVAC coil temperature (T_{HVAC}) and then multiplied by cooling gain.

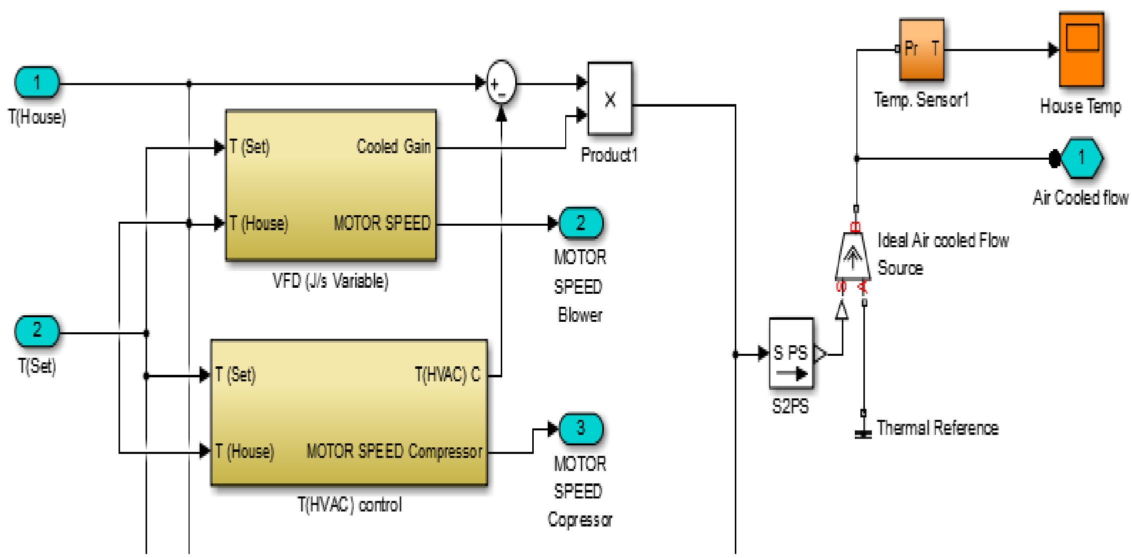


Figure 4.23 Cooler Subsystem on VFD HVAC System

The block diagram of the cooler gain generator (J/s) sub-subsystem is presented in figure 4.24 that contains of two block diagrams, one calculates the cooler gain and another one uses to calculate the desired speed/frequency that delivers to blower motor on VFD system.

Figure 4.24.a displays the block diagram of the subsystem of cooler gain generate based on the thermal dynamic equation 4.33. The inputs of thermodynamic model of cooler are the T_{House} internal temperature for house and $T_{Setting}$ which is the desired temperature for

house. The output of the model is the mass supply airflow $\dot{M}_{HVAC}(t)$ (kg/s) that multiplied by air specific heat C_p (J/kg.K^o) to produce the amount of absorbed heat flow from air house as equation 4.34. Figure 40.b shows the block diagram of the subsystem of desired speed generate based on equations 1.1 and 1.2. The input is the desired Q and the output is the RPM or desired speed/frequency (N or F) with time for the blower motor.

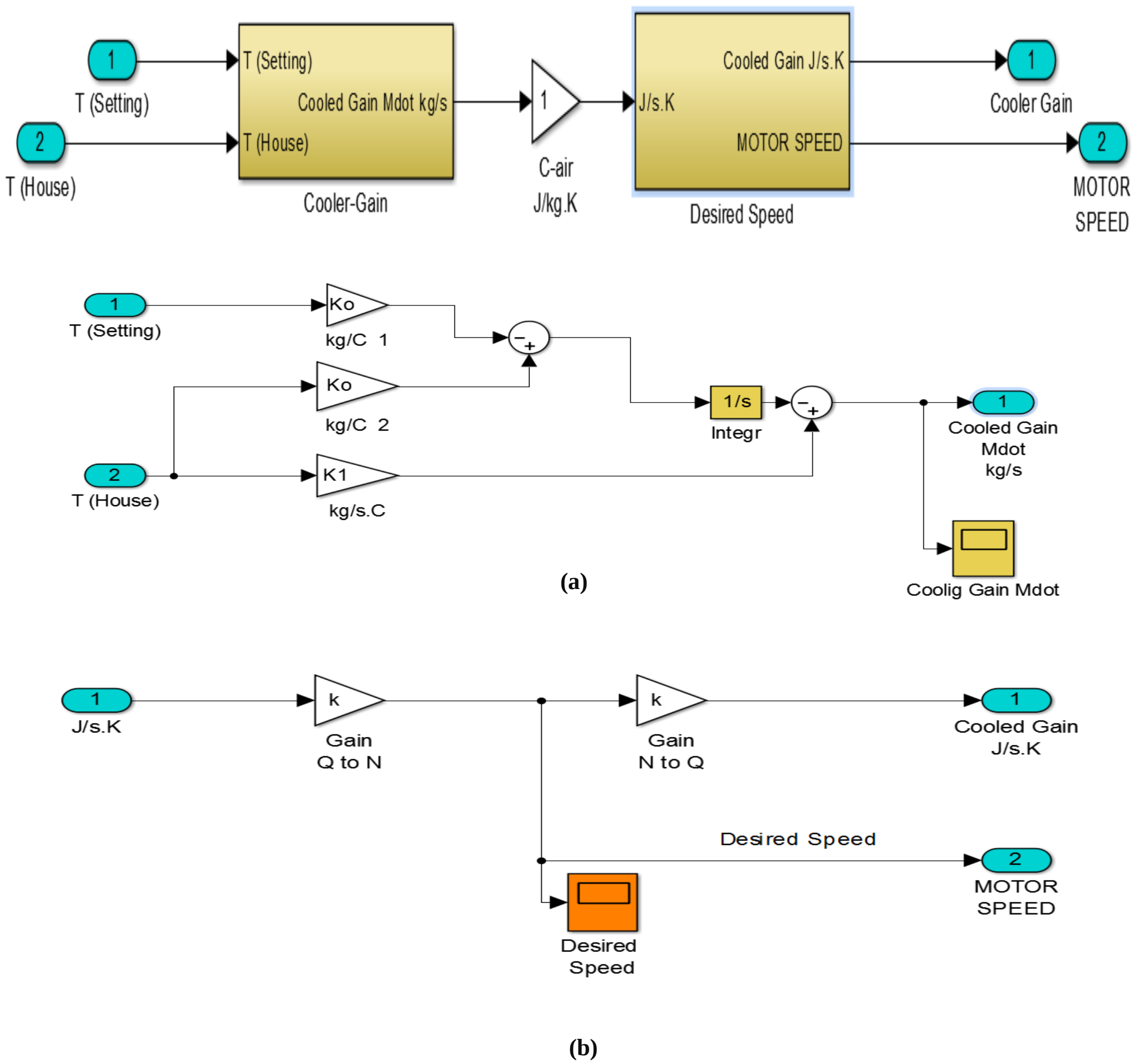
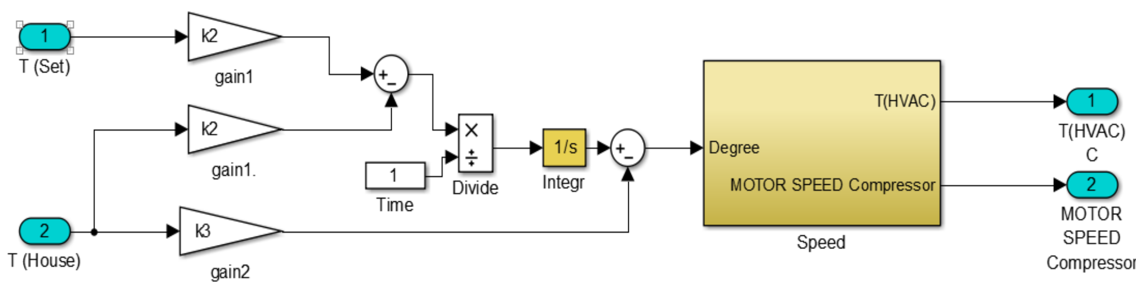


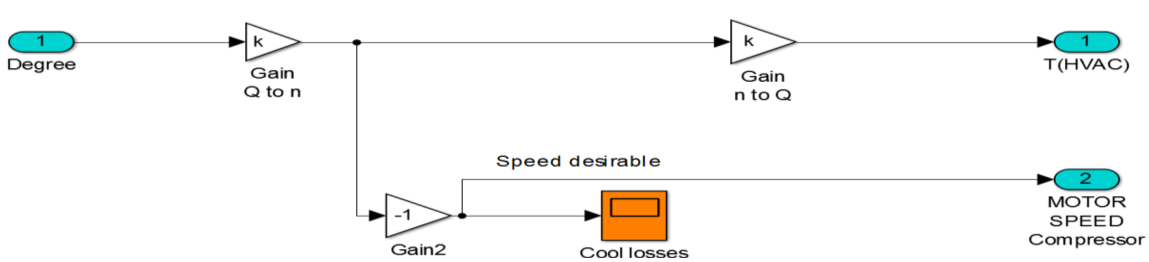
Figure 4.24 Cooler Gain Generator Subsystem.
a: Cooler Gain. b: Desired Blower Speed

The block diagram of the HVAC coil temperature generator (ºC) sub-subsystem is presented in figure 4.25 that also contains of two block diagrams, one calculates the HVAC coil temperature (T_{HVAC}) and another one uses to calculate the desired speed/frequency that delivers to compressor motor on VFD system.

Figure 4.25.a shows the block diagram of the subsystem of HVAC coil temperature generate based on the thermal dynamic equation 4.35. The inputs of thermodynamic model of cooler are the T_{House} internal temperature for house and $T_{Setting}$ which is the desired temperature for house. The output of the model is HVAC coil temperature (ºC) that add to inside air house (T_{House}) based on equation 4.36. Figure 4.25.b shows the block diagram of the subsystem of desired speed generate based on equations 1.1 and 1.2. The input is the desired T_{HVAC} and the output is the RPM or desired speed/frequency (N or F) with time for the compressor motor.



(a)



(b)

Figure 4.25 HVAC Coil Temperature Generator Subsystem.
a: HVAC Coil Temperature. b: Desired Compressor Speed

CHAPTER 5

SIMULATION RESULTS AND DISCUSSION

5.1 Heat Capacity of the House

There are three different parameters contributing to heat gain of house. The heat gained by the house is mostly through the walls, windows, doors and roof. The following sections explained the heat capacity for second order thermal model and upgraded thermal model. The residential house has bedroom, living room, kitchen and bathroom with four windows of glasses.

We need to calculate the gain through each wall, roof, and windows. To determine the heat gained through roof, walls and windows we need to evaluate the thermal conductivity,

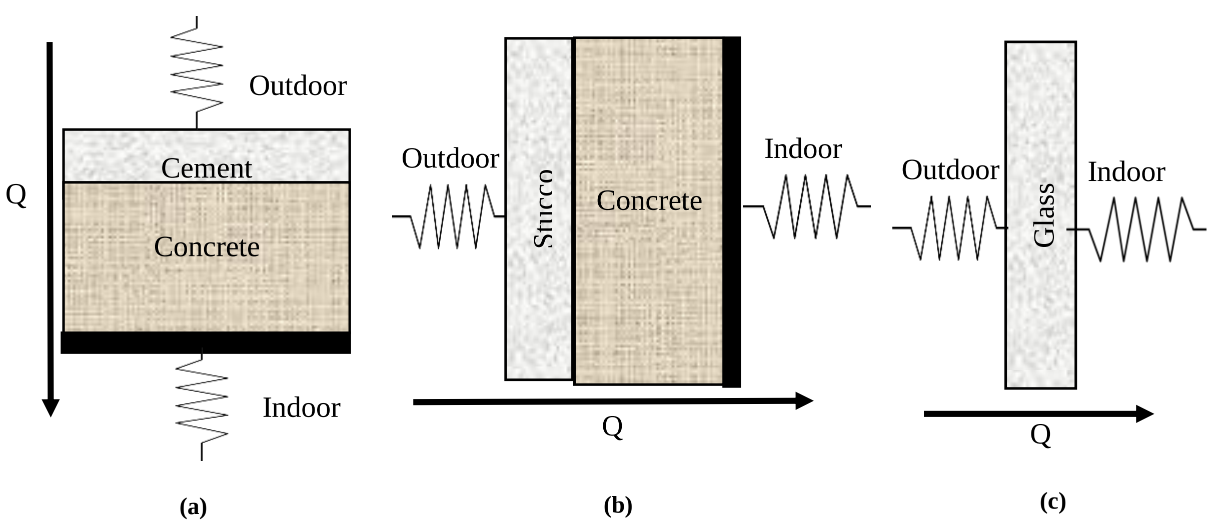


Figure 5.1: a. Roof Section, b. Walls Section, C. Windows Section

convective and irradiative of the section of roof, walls and windows. The section of each roof, walls and windows are presented in figure 5.1.

The thermal conductivity of any house structure type, U, can be found by calculating the thermal resistances for each section of the walls, roof and windows. The thermal conductivity (k) in (W/m.K), heat transfer coefficient (h) in (W/m^2.K) and radiation coefficient (h_{rad}) in (W/m^2.K^4) for material construction used in houses are shown in Table 5.1 [39].

Table 5.1: The Thermal conductivity, Heat Transfer and Radiation Coefficient

<table>
<tr><th>Type</th><th>Thermal conductivity
(h_{cond})
W/m.K</th><th colspan="2">Heat Transfer Coefficient
(h_{conv})
W/m^2.K</th><th>Radiation Coefficient
(h_{rad})
W/m^2.K</th></tr>
<tr><td>Low density Concrete</td><td>0.5</td><td colspan="2">----------------------</td><td>---------------</td></tr>
<tr><td>High density Concrete</td><td>1.0</td><td colspan="2">----------------------</td><td>--------------</td></tr>
<tr><td rowspan="2">Stucco</td><td rowspan="2">0.675</td><td colspan="2">Atmosphere to Stucco</td><td rowspan="2">$4.231*10^{-8}$</td></tr>
<tr><td colspan="2">8.264</td></tr>
<tr><td rowspan="2">Plaster</td><td rowspan="2">0.2</td><td colspan="2">Plaster to in-house Air</td><td rowspan="2">-----------</td></tr>
<tr><td colspan="2">16.95</td></tr>
<tr><td rowspan="2">Cement</td><td rowspan="2">0.71</td><td colspan="2">Atmosphere to Cement</td><td rowspan="2">$5.232*10^{-8}$</td></tr>
<tr><td colspan="2">7.5</td></tr>
<tr><td rowspan="2">Glass</td><td rowspan="2">0.78</td><td>Atmo. To Glass</td><td>glass to in-house Air</td><td rowspan="2">$5.1773*10^{-8}$</td></tr>
<tr><td>32</td><td>25</td></tr>
</table>

First, the wall resistance, which is depending on the wall consisting of stucco, concrete and plaster, then the roof also depends on the roof consisting of cement surfaces, concrete and plaster. The resistance values could be determined from the standard table of thermal properties of common building material, which is summarized in Table 5.2. The table shows the thermal resistances for walls, roof and windows in (K/W).

Table 5.2 The Roof, Walls and Windows Thermal Resistances [40]

Roof Thermal Resistances				
Type	Equation	Area (A) (m^2)	Thickness (x) (cm)	R (K/W)
Inside R $R_{conv(Plaster-House)}$	$R_{conv} = \frac{1}{h_{conv}.A}$	48.45	-------	$1.2177*10^{-3}$
Plaster $R_{cond(Plaster)}$	$R_{cond} = \frac{x}{h_{cond}.A}$	48.45	2	$1.2177*10^{-3}$
High density Concrete $R_{cond(concrete)}$	$R_{cond} = \frac{x}{h_{cond}.A}$	48.45	30	$1.2177*10^{-3}$
Cement $R_{cond(cement)}$	$R_{cond} = \frac{x}{h_{cond}.A}$	48.45	2	$5.8140*10^{-4}$
Outside $R_{conv(Atm-Cement)}$ // $R_{Rad(Cement)}$	$R_{conv} // R_{Rad} = \frac{1}{h_{conv}.A} / / \frac{1}{h_{rad}.A}$	48.45	----	$2.752*10^{-3}$
Walls Thermal Resistances				
Type	Equation	Area A (m^2)	Thickness x (cm)	R (K/W)
Inside R $R_{conv(Plaster-House)}$	$R_{conv} = \frac{1}{h_{conv}.A}$	90	-------	$6.55*10^{-3}$
Plaster $R_{cond(Plaster)}$	$R_{cond} = \frac{x}{h_{cond}.A}$	90	2	$1.1111*10^{-3}$
High density Concrete $R_{cond(concrete)}$	$R_{cond} = \frac{x}{h_{cond}.A}$	90	30	$6.6667*10^{-3}$
Cement $R_{cond(Stucco)}$	$R_{cond} = \frac{x}{h_{cond}.A}$	90	2.5	$4.1111*10^{-4}$

Outside $R_{conv(Atm-Stucco)} // R_{Rad(Stucco)}$	$R_{conv} // R_{Rad} = \frac{1}{h_{conv}.A} // \frac{1}{h_{rad}.A}$	90	----	1.3445*10^{-3}
Windows Thermal Resistances				
Type	Equation	Area A (m^2)	Thickness x (cm)	R (K/W)
Inside R $R_{conv(Glass-House)}$	$R_{conv} = \frac{1}{h_{conv}.A}$	12.1	-------	3.3058*10^{-3}
Glass $R_{cond(Glass)}$	$R_{cond} = \frac{x}{h_{cond}.A}$	12.1	1	1.0596*10^{-3}
Outside $R_{conv(Atm-Glass)} // R_{Rad(Glass)}$	$R_{conv} // R_{Rad} = \frac{1}{h_{conv}.A} // \frac{1}{h_{rad}.A}$	12.1	----	2.5826*10^{-3}

Based on equations (4.13 - 4.18), we will get the thermal resistances R_{11}, R_{12}, R_{21}, R_{22}, R_{31} and R_{32} as shown in the following:

$$R_{11} = R_{conv(Roof-House)} + R_{cond(plaster)} + \frac{R_{cond(concrete)}}{2}$$

$$= \ 6.377655 \times 10^{-3} \text{ (K/W)}$$

$$R_{12} = \frac{R_{cond(concrete)}}{2} + R_{cond(cement)} + R_{conv(Roof-Atm)} \mathbin{/\!/} R_{Rad(cement)}$$

$$= 6.43 \times 10^{-3} \text{ (K/W)}$$

$$R_{21} = R_{conv(Wall-House)} + R_{cond(plaster)} + \frac{R_{cond(concrete)}}{2}$$

$$= 5.1 \times 10^{-3} \text{ (K/W)}$$

$$R_{22} = \frac{R_{cond(concrete)}}{2} + R_{cond(stucco)} + R_{conv(Atm-Wall)} \mathbin{/\!/} R_{Rad(stucco)}$$

$$= 5.098 \times 10^{-3} \text{ (K/W)}$$

$$R_{31} = R_{conv(Wind-House)} + \frac{R_{cond(Glass)}}{2}$$

$$= 3.84 \times 10^{-3} \text{ (K/W)}$$

$$R_{32} = \frac{R_{cond(Glass)}}{2} + R_{conv(Atom-Glass)} \mathbin{/\!/} R_{Rad(Glass)}$$

$$= 3.11 \times 10^{-3} \text{ (K/W)}$$

Where, the U values or heat gains equal to the invers of equivalent resistances:

$$U_{11} = \frac{1}{R_{11}} \quad , \quad U_{12} = \frac{1}{R_{12}}$$

$$U_{21} = \frac{1}{R_{21}} \quad , \quad U_{22} = \frac{1}{R_{22}}$$

$$U_{31} = \frac{1}{R_{31}} \quad , \quad U_{32} = \frac{1}{R_{32}}$$

Where we consider calculating the heat gain for roof, walls and windows. We assumed the internal heat gain is due to the heat convection, Q_{int}. Table 5.3 shows required cooling load for each house, which consists of kitchen, bedroom, and living room [37].

Table 5.3: Required Cooling Load for Houses

Outdoor-Conditions	48 ℃ Dry bulb temp./23.6 ℃ wet bulb temp
Indoor Conditions	24 ℃ / 50 % relative humidity
Lighting	15 W/m^2
Kitchen	1 persons, refrigerator, oven so internal heating dissipation is 1000 W.
Bedroom	2 persons, 1 laptop, so internal heat dissipation is 500 W.
Living/ Dining	2 persons, 1 Laptop, LCD, so the heat dissipation is 500 W.
Building Orientation	West and east big Windows

In building design, thermal mass is a property of the mass of a building that is the ability of a material to absorb and store heat energy. The thermal mass (J/K) is considered from the mass (Kg) of material and its specific heat (J/Kg.K). Table 5.4 presents the thermal mass for in- house air and building construction [40].

Table 5.4: Thermal Mass for Houses

Type	Mass (Kg)	Specific heat (J/Kg.K)	Thermal Mass(J/K)
Air	150.729	1005.4	C_{Air} = 0.151543*10^6
Roof	33430.5	835	C_{Roof} = 27.914*10^6
Walls	62100	835	C_{Walls} = 51.8535*10^6
Windows	412.5	840	$C_{Windows}$ = 0.3465*10^6

Simulation Data Generated for the thermal house model and HVAC systems presented in Table 5.5.

Table 5.5: Simulation Data Generated for the thermal house model and HVAC systems

Item	Amount	Unit
Length of house	8.5	m
Width of house	5.7	m
Wall area	229.3	m^2
Roof area	48.45	m^2
Number of windows	4	-----------
Height of window 1	2.18	m
Width of window 1	2	m
Height of window 2	2.18	m
Width of window 2	2.52	m
Height of window 3	2.18	m
Width of window 3	1	m
Height of window 4	2.18	m
Width of window 4	1	m
Window area	14.2136	m^2
U_{11}	156.797	*W/K*
U_{12}	155.536	*W/K*
U_{21}	196.0784	*W/K*
U_{22}	196.502	*W/K*

<table>
<tr><td>U_{31}</td><td colspan="3">260.718</td><td>W/K</td></tr>
<tr><td>U_{32}</td><td colspan="3">312.298</td><td>W/K</td></tr>
<tr><td>C_{Air}</td><td colspan="3">$0.101273*10^6$</td><td>J/ K</td></tr>
<tr><td>C_{Roof}</td><td colspan="3">$27.914*10^6$</td><td>J/ K</td></tr>
<tr><td>C_{Walls}</td><td colspan="3">$51.8535*10^6$</td><td>J/ K</td></tr>
<tr><td>$C_{Windows}$</td><td colspan="3">$0.3465*10^6$</td><td>J/ K</td></tr>
<tr><td>T_{HVAC}</td><td colspan="3">11</td><td>℃</td></tr>
<tr><td rowspan="6">M_{dot}</td><td>Air Speed two Outlet Ducks</td><td>4.19</td><td>2.24</td><td>(m/s)</td></tr>
<tr><td>Tow Outlet Ducks Area</td><td>$0.4 \times 0.35 = 0.14$</td><td>$0.76 \times 0.14 = 0.1064$</td><td>$(m^2)$</td></tr>
<tr><td>Volume Flow Rate</td><td>0.5866</td><td>0.23833</td><td>(m^3/s)</td></tr>
<tr><td>Air Mass flow</td><td colspan="2">$(0.5866+0.23833) \times 1.225 = 1.011$</td><td>(kg/s)</td></tr>
<tr><td>ON/OFF Cycle</td><td colspan="2">≅ 3600</td><td rowspan="2">kg/h</td></tr>
<tr><td>VFD System</td><td colspan="2">2200-3600</td></tr>
<tr><td>Air Density</td><td colspan="3">1.225</td><td>Kg/m^3</td></tr>
<tr><td>$T_{initial}$</td><td colspan="3">25</td><td>℃</td></tr>
<tr><td>$T_{Setting}$</td><td colspan="3">24</td><td>℃</td></tr>
<tr><td rowspan="2">Power use</td><td>Compressor + Condenser</td><td colspan="2">4.239</td><td rowspan="2">KW</td></tr>
<tr><td>Blower_Fan</td><td colspan="2">0.82</td></tr>
</table>

5.2 Climate of Dhahran, Saudi Arabia

The climate in Saudi Arabia is marked by high temperature during the day and low temperature at night. Most of the country follows the pattern of the desert climate. June is the hottest month in Dhahran with an average temperature of 38.66 °C (101.588 °F) and the hottest is Jun and it reached to 54.84°C Table 5.6 and figure 5.2 show the highest recorded, daily mean and lowest recorded temperature in degree in 2015.

Table 5.6 Temperature Data for Dhahran, Saudi Arabia 2015

Months	Recorded High °C	Daily Mean °C	Recorded Low °C
Jan	20.5	15	5
Feb	36.9	23.2	15.5
Mar	38.21	25.02	19.8
Apr	43.54	27.91	23.76
May	51.31	36.99	25.43
Jun	54.84	38.66	27.65
Jul	54.01	39.32	29.05
Aug	52.58	38.05	29.96
Sep	49.8	34.3	26.35
Oct	45.32	31.3	22.9
Nov	39.29	24.36	16.08
Dec	22	16	10

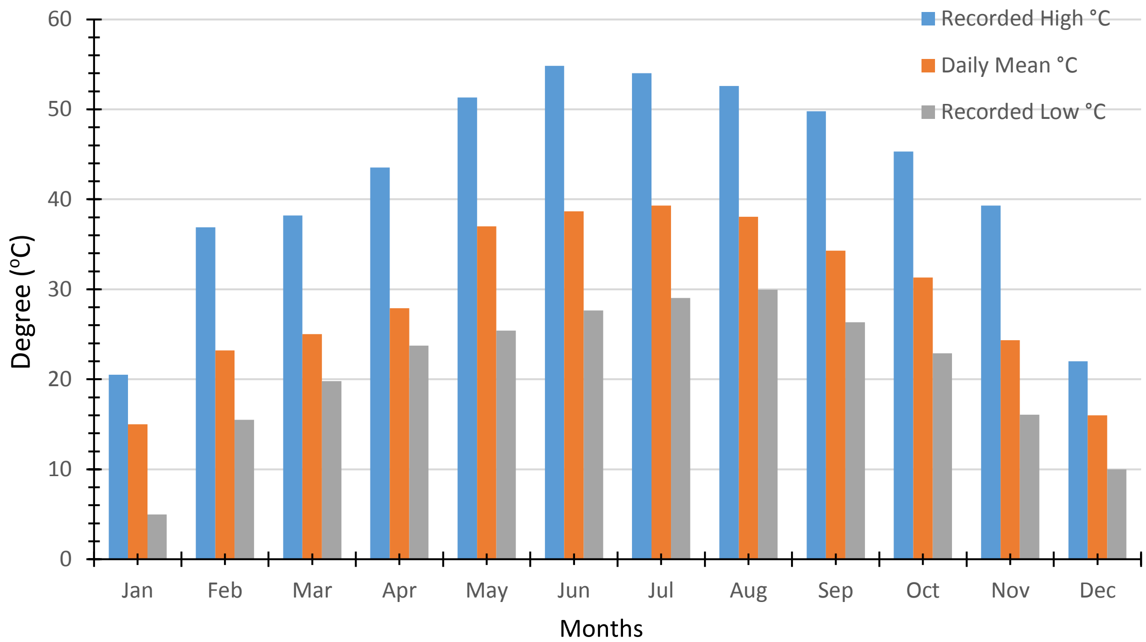


Figure 5.2 Temperature Data for Dhahran, Saudi Arabia 2015

5.3 Simulation of HVAC Systems

Simscape Simulink MATLAB program built to simulate the functionality of ON/OFF and VFD HVAC systems. The simulator used the earlier mathematical formulation of HVAC system chapter 4. The program presented house temperatures (in-house temperature, mid-wall temperature, mid-roof temperature, mid-window temperature) and heat flow from out-house to in-house through roof, walls and windows. Additional information can be provided to simulator when modeling various conditions (e.g., allowable out temperature, in-house occupancy schedules and setting temperature). The simulator also provided the working time (ON time), stopping time (OFF time), the length period, and duty cycle for ON/OFF cycle system. The consume power KWh for ON/OFF and VFD HVAC systems are calculated by MATLAB program.

5.3.1 Simulation ON/OFF Cycle HVAC System

The average duration between adjacent edges of identical polarity within the displayed portion of the in-house signal is defined in the period. Numbers of positive-polarity pulses counted is explained in $+$Pulse. $\pm$Width hours also define in the simulator, which measure the average duration between rising and falling edges of each positive-polarity and the average duration between rising and falling edges of each negative-polarity pulses within the displayed portion of in-house temperature signal. Finally, $\pm$Duty Cycle is the average ratio of pulse width to pulse period for each positive-polarity and the average ratio of pulse width to pulse period for each negative-polarity pulses, which are displayed as $\pm$Duty Cycle.

Figure 5.3 shows the actual ambient temperature, house temperature, mid house construction temperatures for walls, windows and roof. In our simulation, the ambient temperature presented was one of the hottest day in Dhahran, Saudi Arabia, the temperature that reached almost 55 ^{o}C on 2nd of June 2015. The initial temperatures of house air, mid-wall, mid-roof, and mid-windows are 24 ^{o}C, 25 ^{o}C, 25 ^{o}C and 25 ^{o}C respectively. Setting temperature, HVAC cooling temperature and cooling gain and other parameters are explained in Table 5.5. The switch ON/OFF fluctuation of the air conditioner is (+1 and -2) ^{o}C. The duty cycle is variation between 40-50 % when the temperature 37 ^{o}C. As soon as the ambient temperature reached 55 ^{o}C, the air conditioner ran continuously for over 23 minutes until the ambient temperature fell again below 55 ^{o}C. Through the activity of house as light, TV and cooking dinner usually start at 6pm; the air conditioner working is increased for over 18 minutes and 70 % duty cycle. The duration of the cycle for most of the day was between 7-12 minutes. Figure 5.4 is presented the HVAC duty cycle, which is

40 % the lowest and can reach as much as 80 %. HVAC ON time and HVAC OFF time also are presented in figure 5.4.

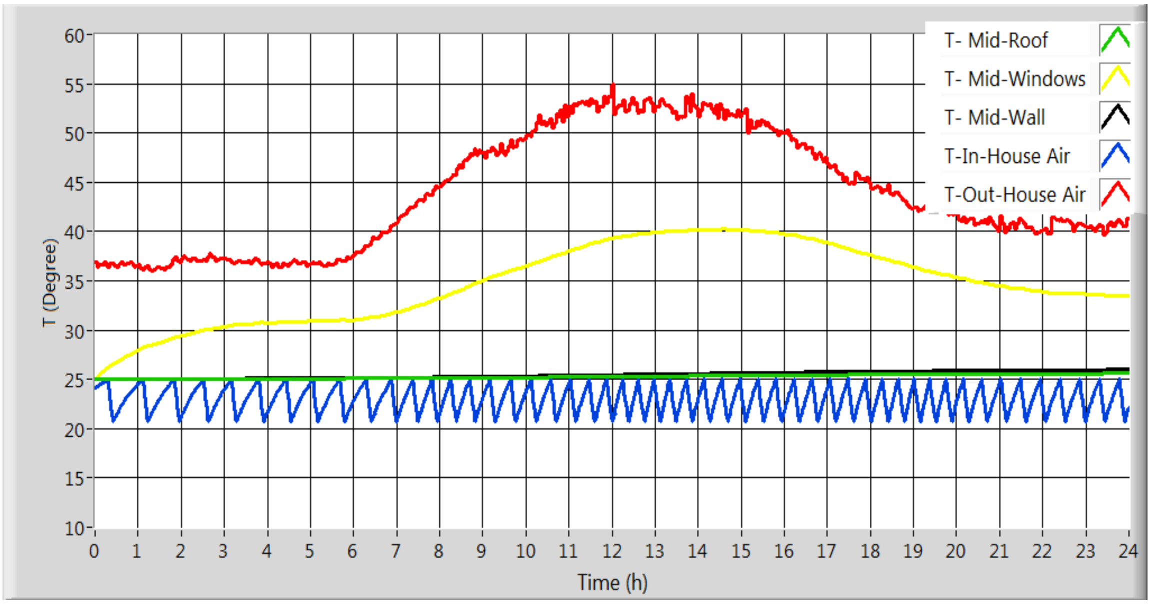


Figure 5.3 Out-House Air Temperature, In-House Air Temperature, Mid-Wall Temperature, Mid-Windows Temperature and Mid-Roof Temperature

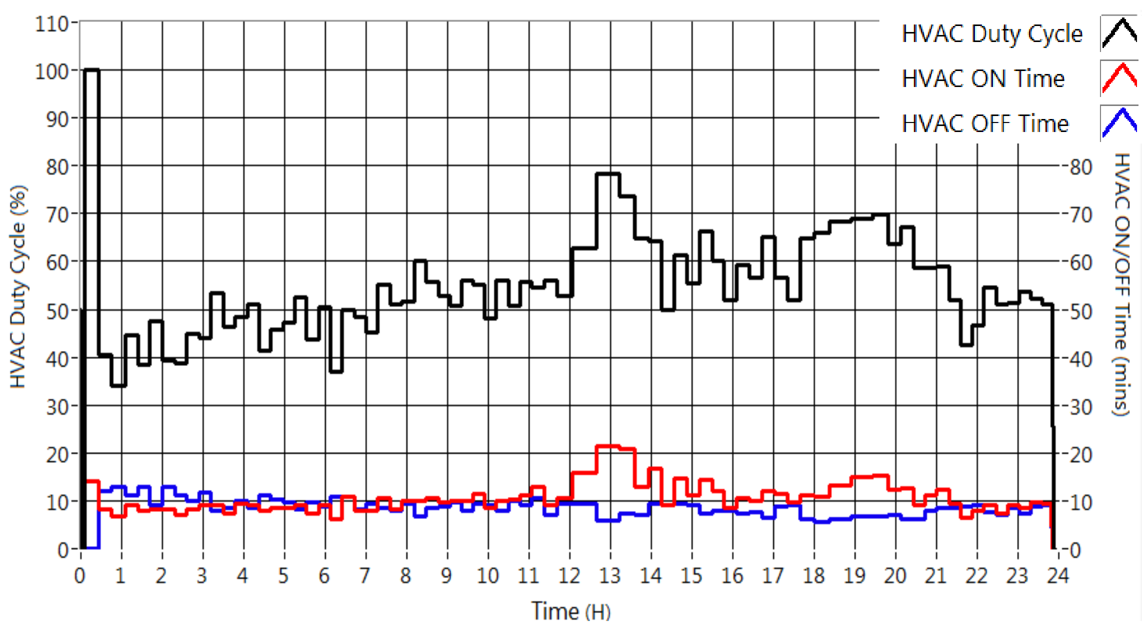


Figure 5.4 HVAC Duty Cycle, HVAC ON Time and OFF Time for One Day

The internal wall, roof and windows surface temperatures for the house are explained in figure 5.5. We show the surface temperature of house construction depend directly on the width. The windows have big area and smallest width so the inside surface windows effect by ambient temperature and it reach at afternoon to 38 ^oC.

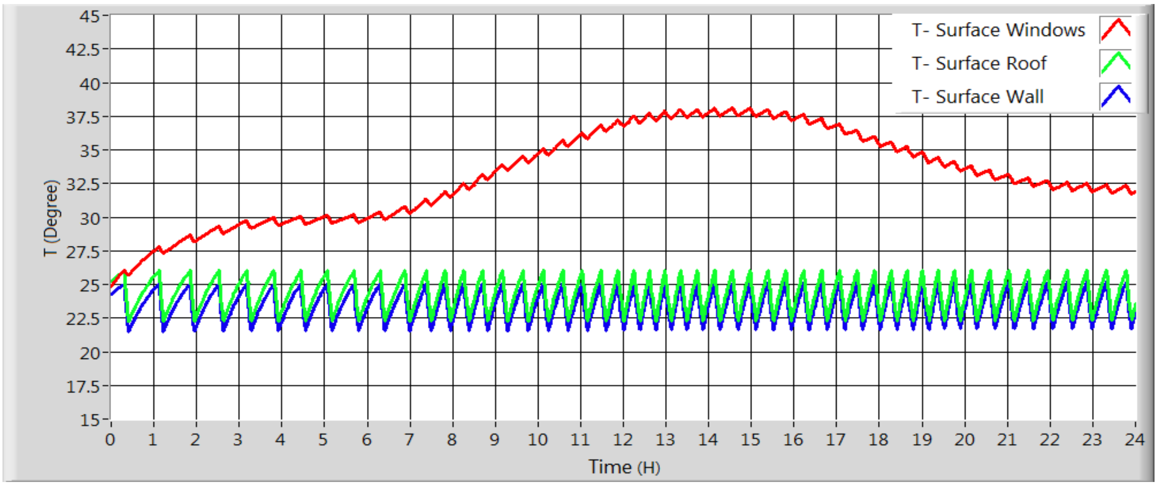


Figure 5.5 Internal Wall, Windows and Roof Surface Temperatures

Eternal heat flows from outhouse to in-house through three ways. Figure 5.6 showed these ways in Btu, heat flows to house through walls, windows and roof and it reached to maximum 60000 Btu in mid-day.

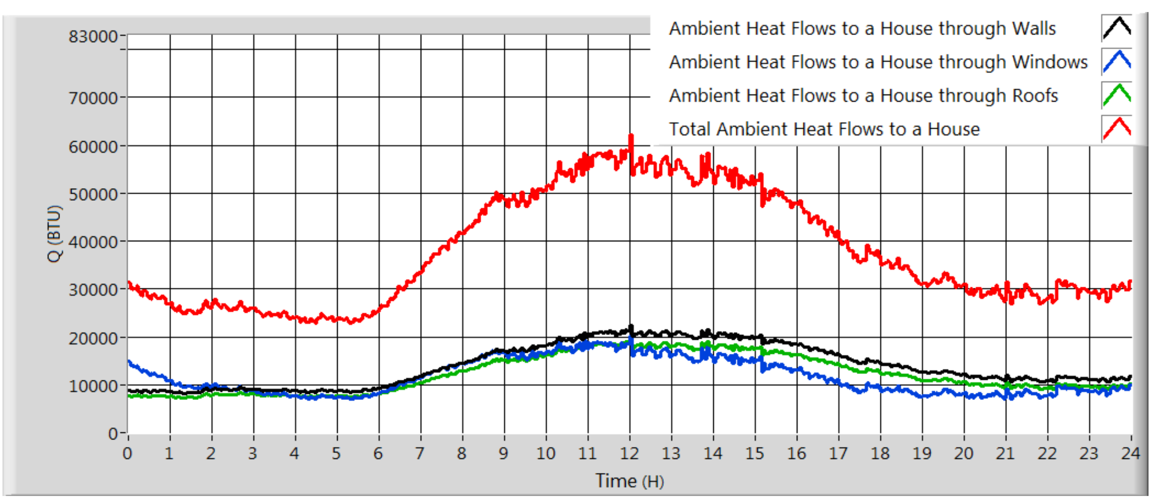


Figure 5.6 Aggregate and Segregate Heat flow from Wall, Windows and Roof

The simulator offered measurements in KW for ambient flow and stored heat. Figure 5.7 shows the heat flow form out to house in KW and the total absorbed heat for each wall, roof and windows. Where the total ambient heat flow and absorbed heat in house construction reach to 11 KJ/s (37510 Btu) and 8 KJ/s (27280 Btu) respectively at 12 pm. Heat passed to house through house construction (10230 Btu) and activity loads are presented in figure 5.8. Cooling flow or absorbed air house heat displayed in figure 5.8.

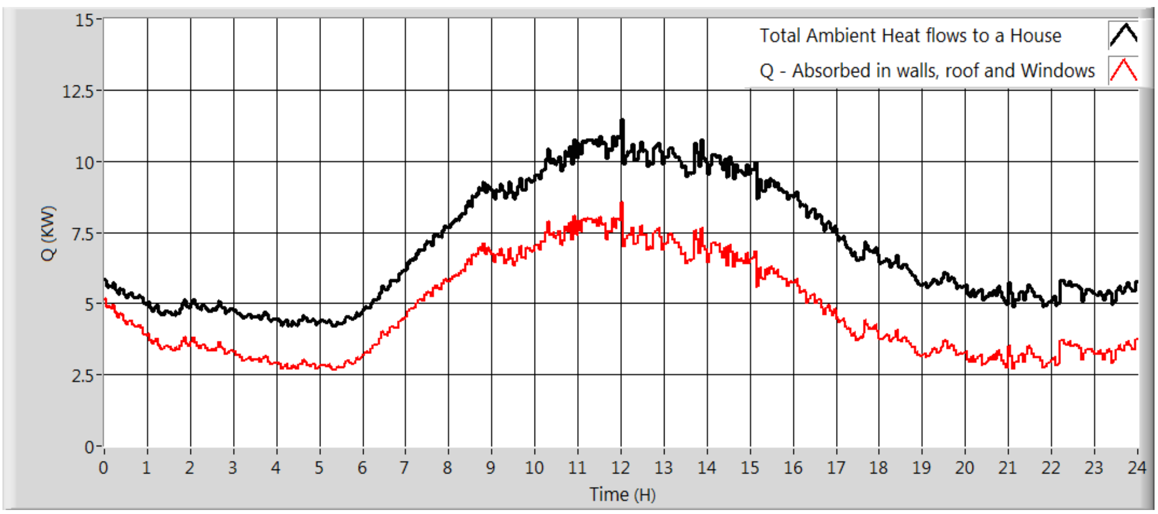


Figure 5.7: Total External Heat Flow and the Stored Heat in Wall, Windows and Roof

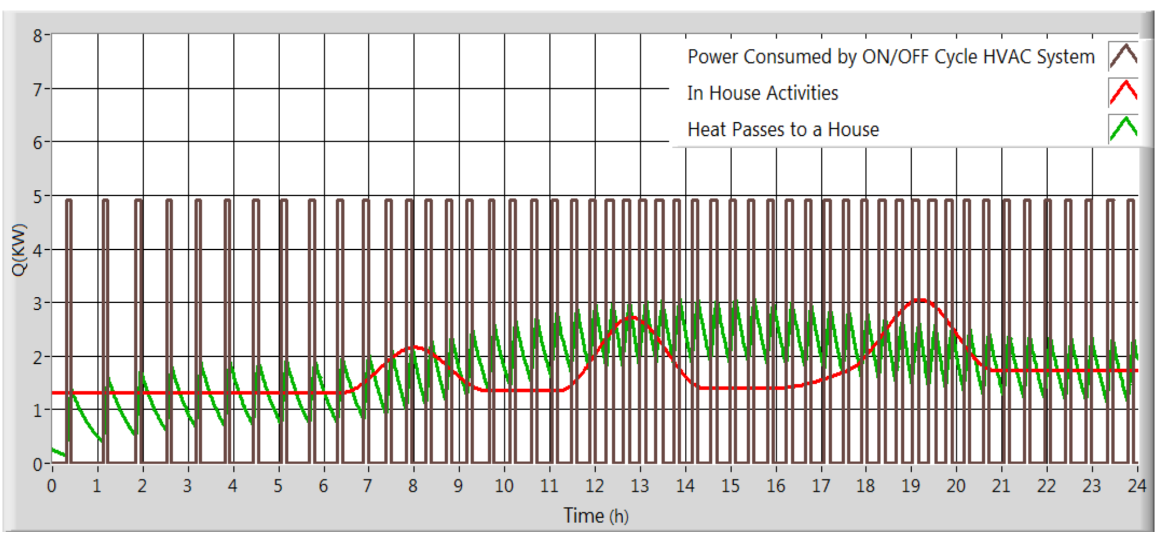


Figure 5.8 Cooler Flow, Activity Heat Flow and Heat Flow passes to House through Wall, Windows and Roof for One Day

The summery results of energy consumption on 2 June 2015 is explained in Table 5.7. Average working period of one cycle is 10.719 mins and number of ON pulse is around 71 pulses. Therefore, the duration of the conditioner unit is ON 6.924 h.

Table 5.7 Summary of Energy Used on 2 June 2015

The average period		10.719 mins	
Numbers of positive-polarity (+pulses)		71	
The average ON Width		5.851 mins	
The average OFF Width		4.868 mins	
The duration ON/OFF unit work		8.77 h	
HVAC Energy used (Auto_Fan_ Mode)	Compressor +Condenser	36.834 KWh	43.850 KWh
	Blower_Fan	7.016 KWh	
HVAC Energy used (On_Fan_Mode)	Compressor +Condenser	36.834 KWh	56.034 KWh
	Blower_Fan	19.200 KWh	

Now if we left all the parameters unchanged and only make the simulation for three days 21st, 22nd, and 23rd in September 2015. We noticed the behavior house temperatures with our simulator.

Figure 5.9 shows the actual ambient temperature, house temperature, mid house construction temperatures for walls, windows and roof. In simulation, the ambient temperature was hottest day in Dhahran, Saudi Arabia, the temperature reached to 48 ^{o}C. The initial temperatures of house, mid-wall, mid-roof and mid-windows are 24 ^{o}C, 25 ^{o}C, 25 ^{o}C and 25 ^{o}C respectively. Setting temperature, HVAC cooling temperature and cooling gain and other parameters are explained in Table 5.5.

The switch ON/OFF fluctuation of the air conditioner is (+1 and -2) ^{o}C. The duty cycle is variation between 30-50 % when the ambient temperature around 32.5 ^{o}C. As soon as the ambient temperature reached 48 ^{o}C, the air conditioner ran continuously for over 22 minutes until the ambient temperature fell again below 48 ^{o}C. Through the activity of house as light, TV and cooking dinner usually start at 6pm; the air conditioner working is increased for over 15 minutes and 65 % duty cycle. The duration of the cycle for most of the days were between 5-9 minutes. Figure 5.10 is presented the HVAC duty cycle, which is 35 % the lowest and can reach as much as 70 %. HVAC ON time and HVAC OFF time are presented in figure 5.10.

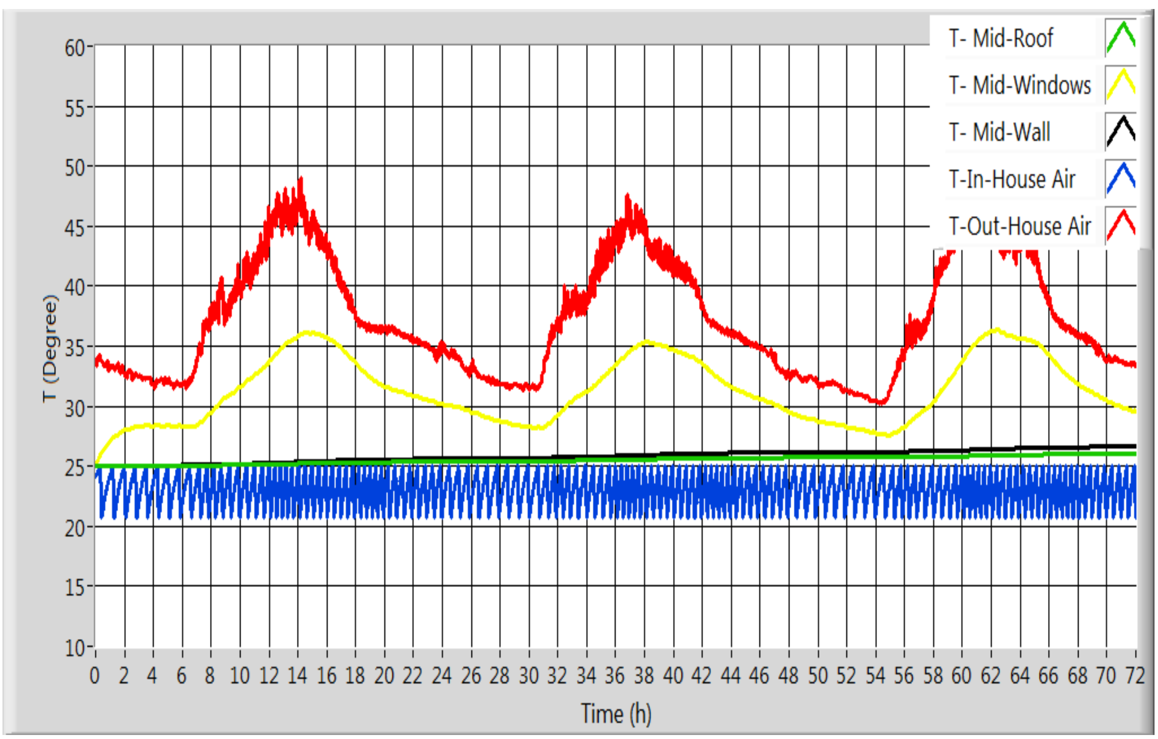


Figure 5.9 Out-House Air Temperature, In-House Air Temperature, Mid-Wall Temperature, Mid-Windows Temperature and Roof Temperature for Three Days

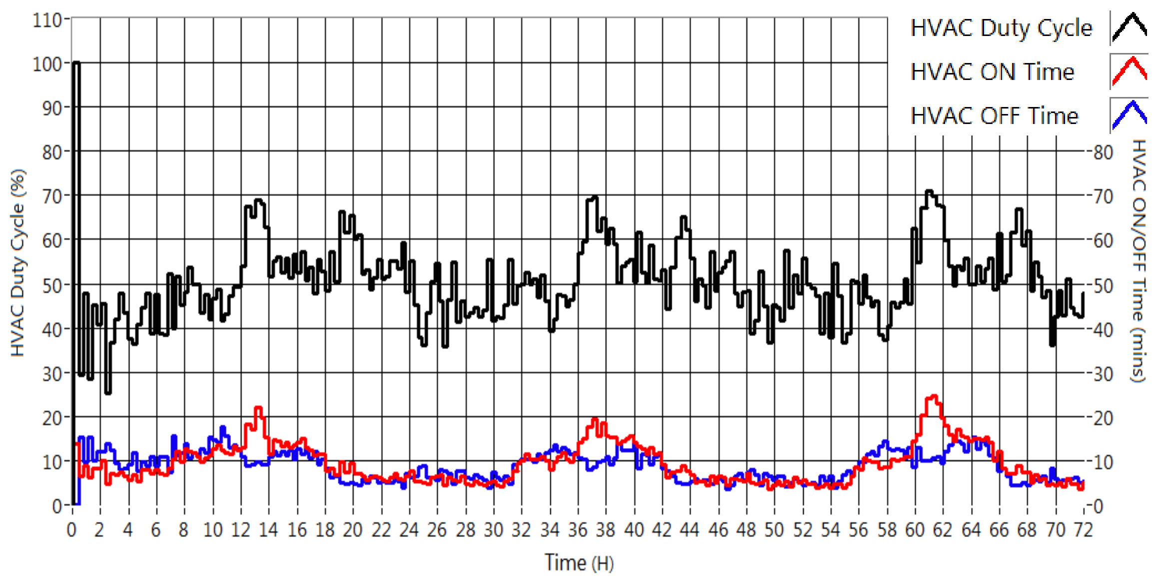


Figure 5.10 HVAC Duty Cycle, HVAC ON Time and OFF Time for Three Days

The wall, roof and windows surface temperatures for the house are explained in figure 5.11. We show the surface temperature of house construction depend directly on the width. The windows have big area and smallest width so the inside surface windows effect by ambient temperature and it reached at afternoon to 34 ^{o}C.

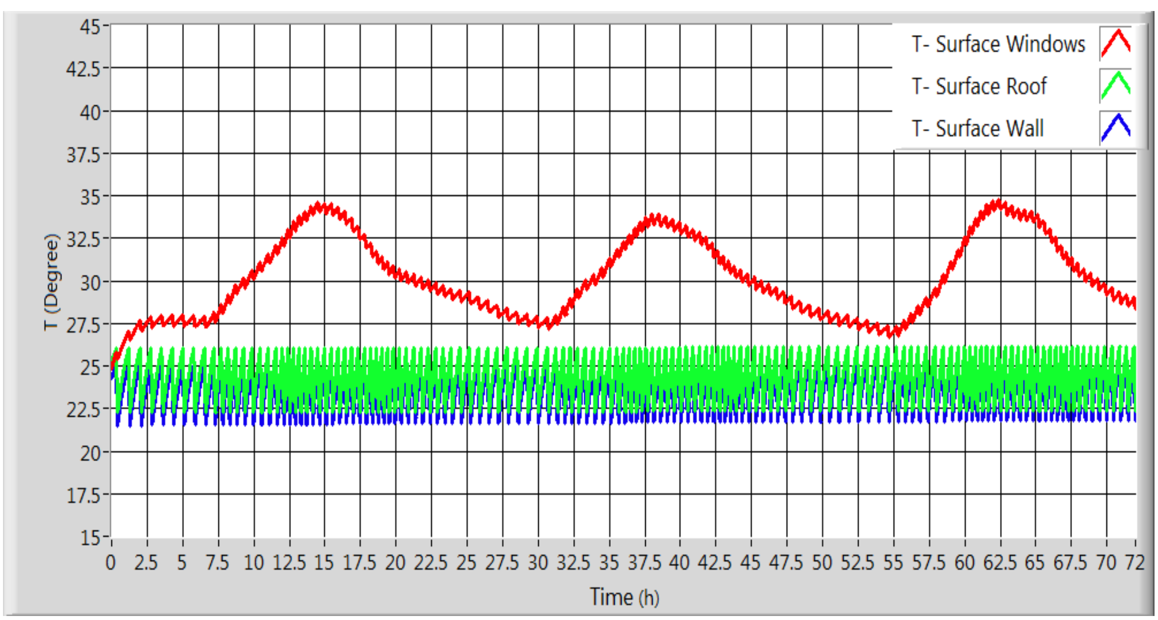


Figure 5.11 Internal Wall, Windows and Roof Surface Temperatures

External flow heat from outhouse to in-house divided to three ways. Figure 5.12 displayed these ways in Btu, heat flow through walls, windows and roof that reaches to 50000 Btu maximum at 12 pm.

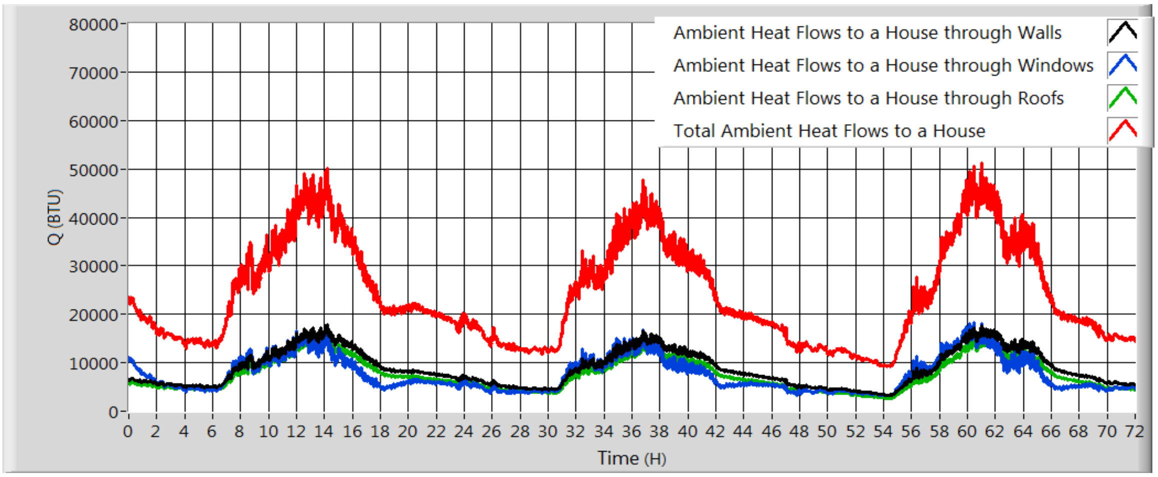


Figure 5.12 Aggregate and Segregate Heat flow from Wall, Windows and Roof

The simulator is offered measurements in KJ/s for ambient flow and stored heat. Figure 5.13 shows the heat flow form out to house in KJ/s and the total absorbed heat for each wall, roof and windows. The pass heat to house through house construction and activity loads are presented in figure 5.14. Cooling flow or absorbed air house heat also is displayed in figure 5.14.

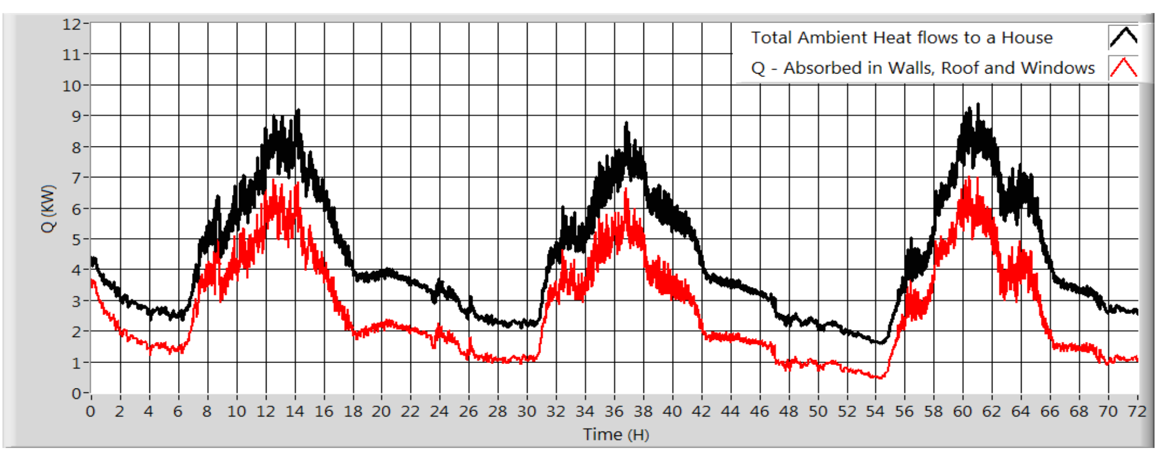


Figure 5.13 Total External Heat Flow and the Stored Heat in Wall, Windows and Roof

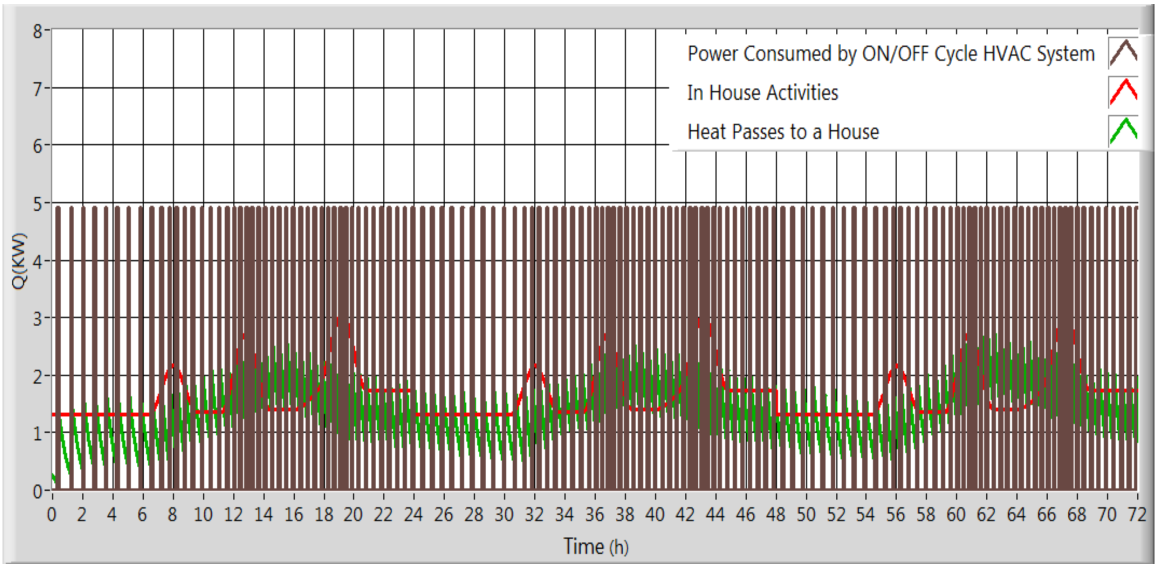


Figure 5.14 Cooler Flow, Activity Heat Flow and Heat Flow passes to House through Wall, Windows and Roof for Three Days

The summery results of energy consumption used on three days of September 2015 is explained in Table 5.8. Average working period of one cycle is 13.655 mins and the number of ON pulse is around 249 pulses. So the duration of the conditioner unit is ON 20.771 h and OFF 51.229 h.

Table 5.8 Summery of Energy used on three days of September

The average period		13.655 mins	
Numbers of positive-polarity (+pulses)		249	
The average ON Width		5.970 mins	
The average OFF Width		8.640 mins	
The duration ON/OFF unit work		25.771 h	
HVAC Energy used (Auto_Fan_ Mode)	Compressor +Condenser	108.238 KWh	128.433 KWh
	Blower_Fan	20.617 KWh	
HVAC Energy used (On_Fan_Mode)	Compressor +Condenser	108.238 KWh	165.838 KWh
	Blower_Fan	57.600 KWh	

5.3.2 Simulation VFD HVAC System

Figure 5.15 shows the actual ambient temperature, house temperature and mid house construction temperatures for walls, windows and roof. In our simulation, the ambient temperature presented was one of the hottest day in Dhahran, Saudi Arabia, the temperature that reached almost 55 ^{o}C on the second of June 2015. The initial temperatures of house, mid-wall, mid-roof and mid-windows are 24 ^{o}C, 25 ^{o}C, 25 ^{o}C and 25 ^{o}C respectively. HVAC cooling temperature and cooling gain and other parameters are explained in Table 5.5. The system has not fluctuation of the air conditioner. As soon as the ambient temperature reached 55 ^{o}C, figure 57, the air conditioner ran continuously and then cooling flow increases smoothly up to 100% of flow to save temperature on setting point 24 ^{o}C as it presented in figure 5.16. Through the activity of house as light, TV and cooking dinner usually start at 6pm as showing in figure 5.17, the air conditioner working is increased for over 70 % and then it goes up to reach 90 % at dinner time 8pm.

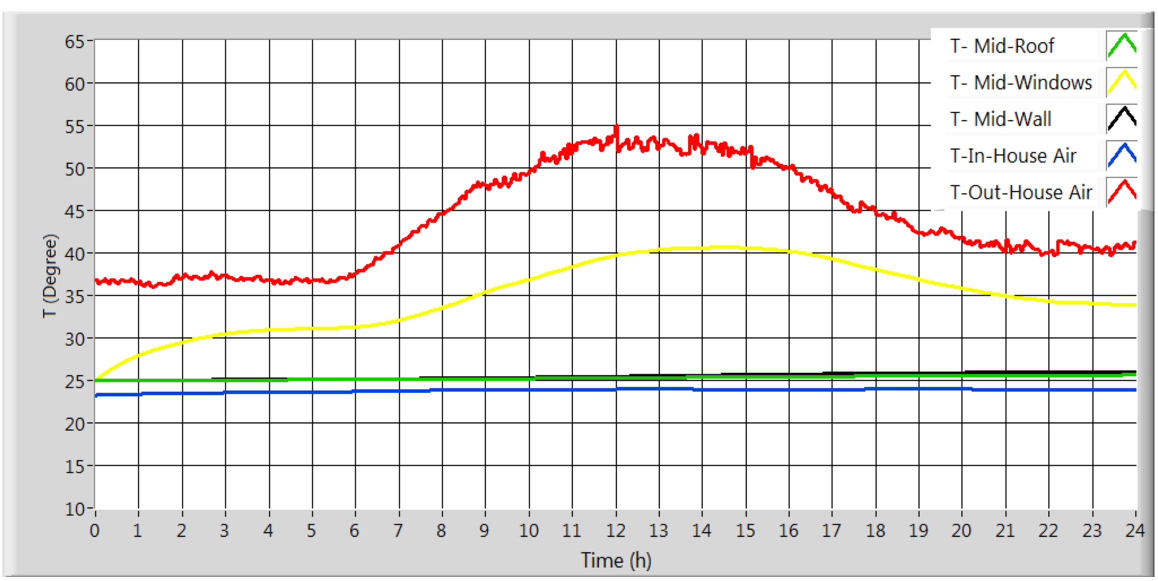


Figure 5.15 Out-House Air Temperature, In-House Air Temperature, Mid-Wall Temperature, Mid-Windows Temperature and Roof Temperature for One Day

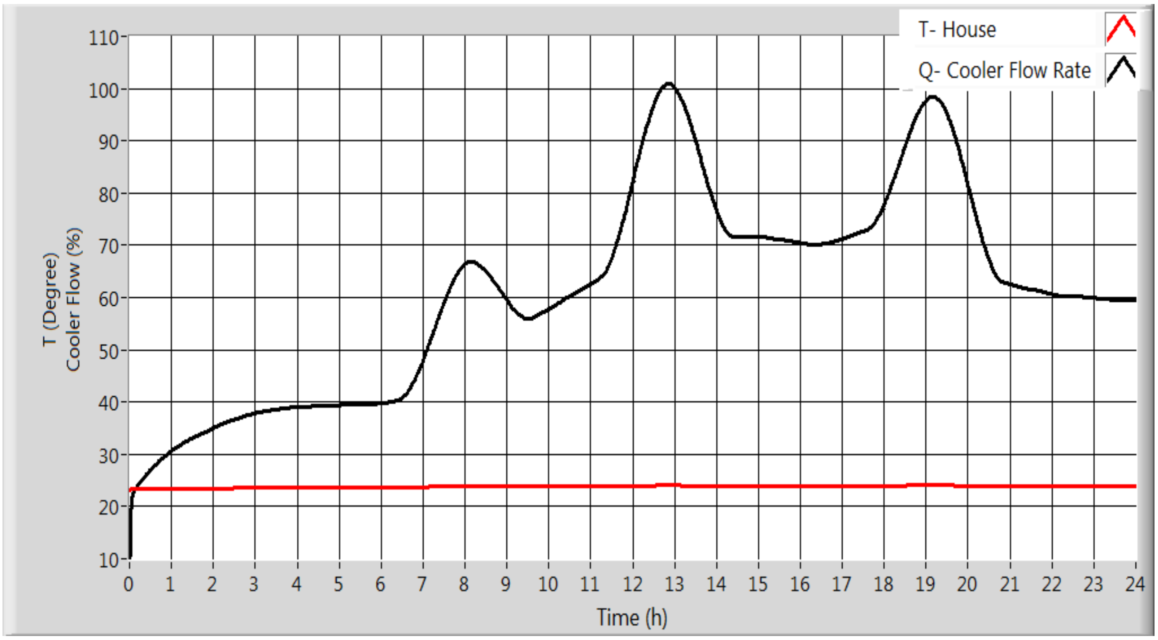


Figure 5.16 Variable Cooling Air Flow rate form VFD HVAC System and In-House Air Temperature for One Day

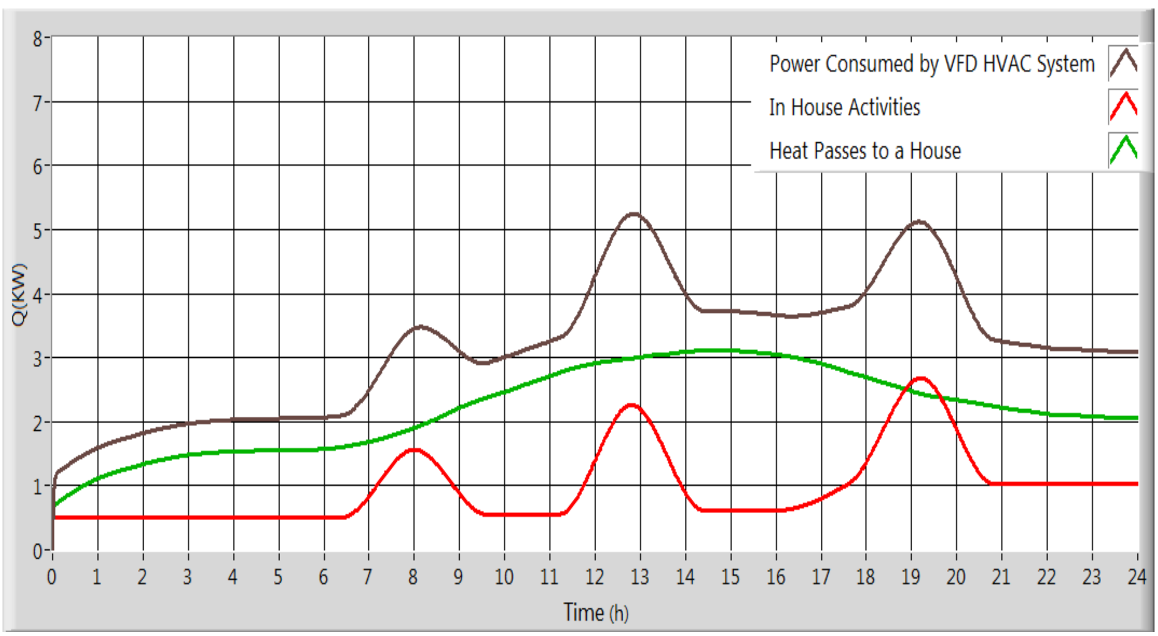


Figure 5.17 Cooler Flow, Activity Heat Flow and Ambient Heat passes to House for One Day

The energy used for VFD HVAC unit was calculated by integrating the area under cooled airflow curve (KW) in figure 5.17 and it gave 33.373 KWh.

Similarly, if we left all the parameters unchanged and only make the simulation for three days 21st, 22nd, and 23rd of September 2015. We noticed the behavior house temperatures with our simulator.

Figure 5.18 shows the actual ambient temperature, house temperature and mid house construction temperatures for walls, windows and roof. In our simulation, the ambient temperature presented was one of the hottest day in Dhahran, Saudi Arabia, the temperature that reached almost 55 ^{o}C on the second of June 2015. The initial temperatures of house, mid-wall, mid-roof and mid-windows are 24 ^{o}C, 25 ^{o}C, 25 ^{o}C and 25 ^{o}C respectively. HVAC cooling temperature and cooling gain and other parameters are explained in Table 5.5. The system has no fluctuation of the air conditioner. As soon as the ambient temperature reached 48 ^{o}C, figure 5.19, the air conditioner ran continuously and then cooling flow increases smoothly up to 90% of flow to save temperature on setting point 24 ^{o}C as it presented in figure 5.19. Through the activity of house as light, TV and cooking dinner usually start at 6pm as showing in figure 5.20, the air conditioner working is increased for over 60 % and then it goes up to reach 88% at dinner time 8pm. The lowest variable airflow rate is 30%.

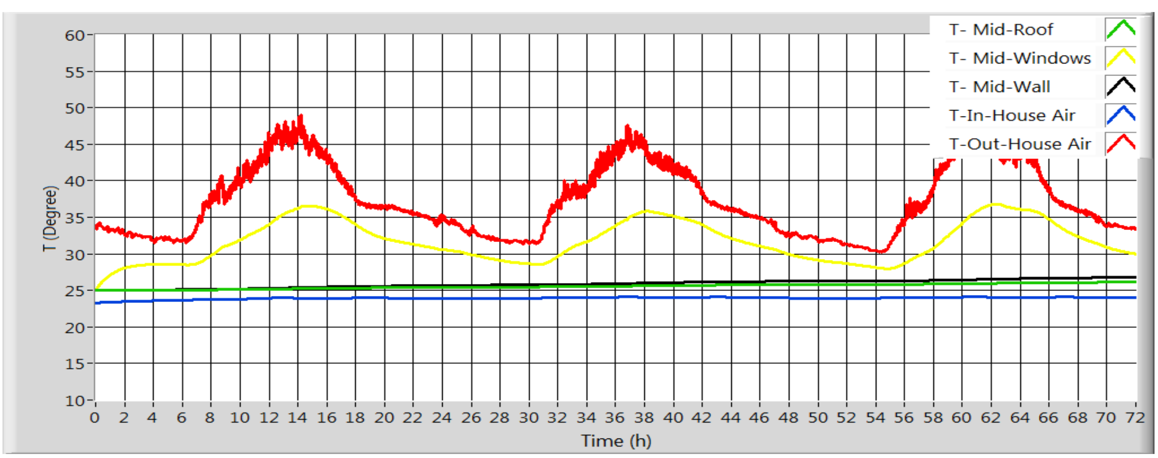


Figure 5.18 Out-House Air Temperature, In-House Air Temperature, Mid-Wall Temperature, Mid-Windows Temperature and Roof Temperature for Three Days

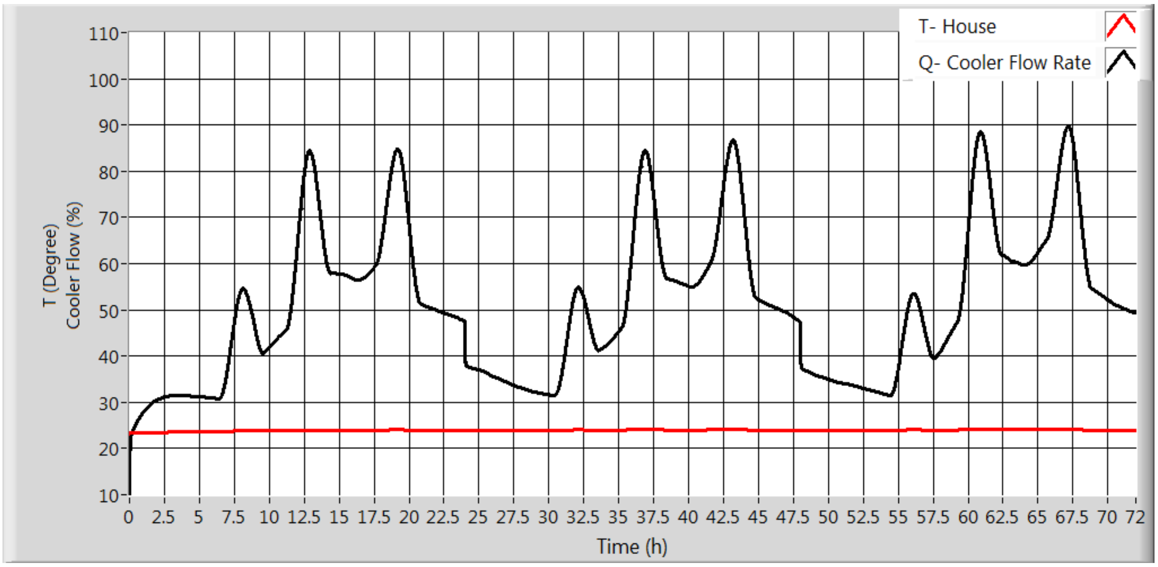


Figure 5.19 Variable Cooling Air Flow rate form VFD HVAC System and In-House Air Temperature for three days

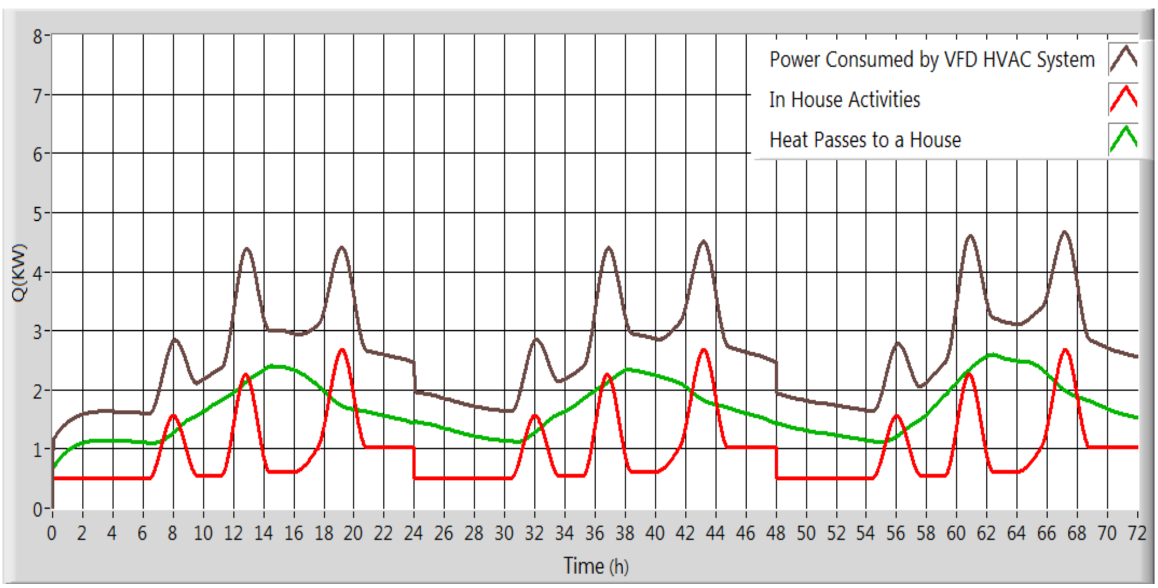


Figure 5.20 Cooler Flow, Activity Heat Flow and Ambient Heat passes to House for Three Days

The energy consumption for VFD HVAC unit was calculated by integrating the area under airflow curve (KW) in figure 5.21 it gave 96.5 KWh for three days.

5.4 Compare Energy Consumption for Both HVAC Systems

Table 5.9 explained the summary results of energy consumption for the hottest day on 2nd of June and three days (21st, 22nd, & 23rd) in September 2015.

If we compare energy used in ON/OFF and VFD HVAC systems on 2nd of June, we found that energy saved in this particular day is 23.9 % and it displayed in figure as red cooler. Similarly, if we compare identical three days (21st, 22nd, & 23rd) in September, 2015, which discussed in last section. We found energy saved in this particular day is 24.63 %.

Table 5.9 Comparison energy used for ON/OFF and VFD HAC Systems

Days	ON/OFF Cycle HVAC System	VFD HVAC System	Energy Saving (%)
	Energy used (KWh)	Energy used (KWh)	
June, 2nd 2015	43.85	33.373	23.89
Three days (21st, 22nd, & 23rd) in September, 2015	128.433	96.5	24.63

Table 5.10 explained the summary results of energy consumption for one-year study. Both ON/OFF cycle HVAC and VFD HVAC systems used for same conditions. Average working period of one cycle and number of ON pulse also are displayed in the table. The power used in KWh present for both ON/OFF cycle HVAC and VFD systems HVAC. The hottest months are used, the higher ON duty cycle per month. The comparison the energy

consumption for both systems is shown in figure 5.21. Table 5.9 shows the highest save of energy occur on May and the energy saving per month is explained in figure 5.22.

Table 5.10: Comparison energy used for ON/OFF and VFD HAC Systems for several months

Months	ON/OFF Cycle HVAC System						VFD HVAC System	Energy Saving (%)
	The Average period (mins)	Numbers of ON Pulses	The average ON Width (mins)	The average OFF Width (mins)	The average ON Duty Cycle (%)	Energy used per Month (KWh)	Energy used per Month (KWh)	
May 2015	14.255	1906	5.352	08.903	53.072	939.276	602.358	35.87
June 2015	14.487	2190	5.851	08.636	54.15	1067.808	771.384	27.76
July 2015	14.503	2309	5.860	08.643	54.380	1127.562	823.120	27.00
Aug. 2015	14.424	2208	5.795	8.6296	53.166	1066.280	769.641	27.82
Sep. 2015	15.752	2150	5.179	10.546	53.333	927.904	662.895	28.56
Oct. 2015	18.835	1540	5.063	13.772	51.633	649.752	438.972	32.44
Nov. 2015	25.663	1125	4.772	20.891	49.18	475.500	288.058	39.42
Mar.2016	22.274	1290	4.871	17.402	49.380	542.20	292.408	45.10
Apr. 2016	17.048	1450	5.010	12.038	50.342	555.00	331.200	40.32

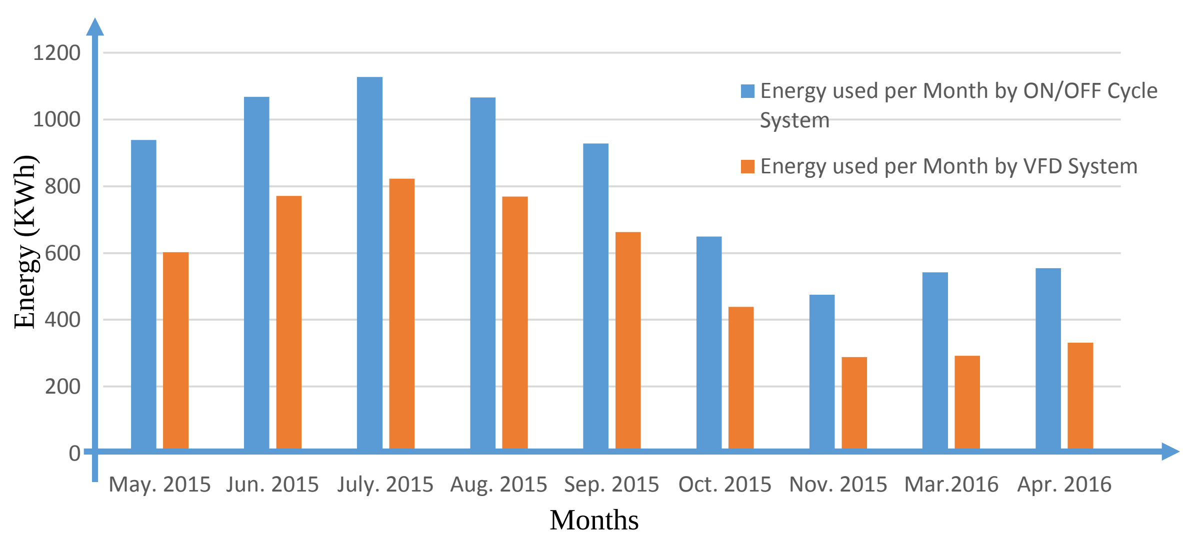


Figure 5.21 Energy Consumption for ON/OFF Cycle and VFD HVAC Systems

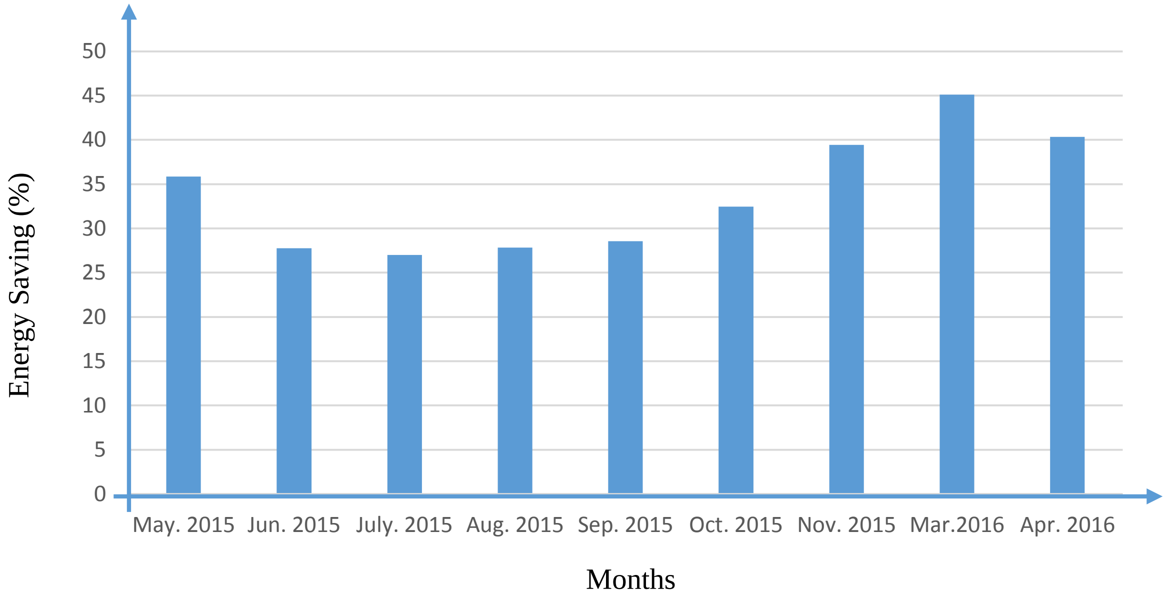


Figure 5.22 Energy Saving Rate per Month

CHAPTER 6

EXPERIMENTAL SETUP

6.1 Heating-Cooling System Characteristic

Several factors interact between a heating/cooling system and thermal demand in building:

-Weather.

-Occupant‘s behavior.

-Economic status of occupants.

-Physical properties of building.

-Characteristic of heating/cooling system.

Thermal demand in buildings are space heating, hot water demand, and cooking. Space heating depends on time of the year, time of the day, housing design, occupancy pattern, and performance heating system. Several factors influence space heating:

- Physical characteristic of the house:

- U-values.

- Thermal capacity.

- Internal heat transfer.

- Infiltration rate.

- External weather conditions:

- Temperature.

- Solar radiation.

- Wind speed

- Characteristic of heating system:

- System efficiency.

-Time constant.

- Control.

- User requirements:

-Temperature level.

-Window opening.

- Internal gain:

-Due to electrical appliance and occupant' s behavior.

6.1.1 Thermal Envelope of a House

The ''thermal envelope''may be described as the thermal barrier of a building to resist external temperatures ''hot or cold'' penetrating to the inside of a building which in turn influences the heating and cooling systems required. Thermal envelope of a home has a conductance U_A through which heat flows from the room air temperature to T_A to the outdoor temperatureT_0. U_A is the sum of all parallel heat flow path through the envelope of the house (walls, doors, roofs, ceilings, and infiltration airflow, etc.). The performance of a thermal house envelope depends on:

1. Insulation value / U- Value
2. Air Leakage/ infiltration
3. Thermal mass / ability to store energy

6.1.2 General Project Data Input

General project information for houses 3305 & 3307 as the floor plane is displayed in next figures. The floor plan and trees position with sun orbit are explained in the figures 6.1. The duct plan and windows number and location are shown in figure 6.2. Each house consists of two rooms (one living room and one bedroom), kitchen and bathroom. The houses location and ambient parameters are indicated in Table 6.1.

Table 6.1 The Environment Parameters for Project Location

Weather reference city	Dhahran, Saudi-Arabia
Project Location	KFUPM, Guest-Houses 3305&3307
Barometric pressure:	1007.652 mbar
Altitude	22.86 meters
Latitude and Longitude	26.288768 and 50.114103

6.1.3 Air Conditioning Units of the Houses

In the tropical area and the summer time specially, high relative humidity, elevated air temperatures and bright sunshine can sometimes combine to produce an uncomfortable indoor environment. An air-conditioning system can provide comfort for occupants by lowering the air temperature and the humidity level in the home [41].

Two A/C units with two technics are used in this project. Traditional ON/OFF cycle A/C unit is installed in house #3305 and VFD A/C unit is installed in house #3307. The two units have some common terms we will come across when comparing and determining the best choice for air conditioners:

Figure 6.1 Floor Plan for 3305 and 3307 Houses

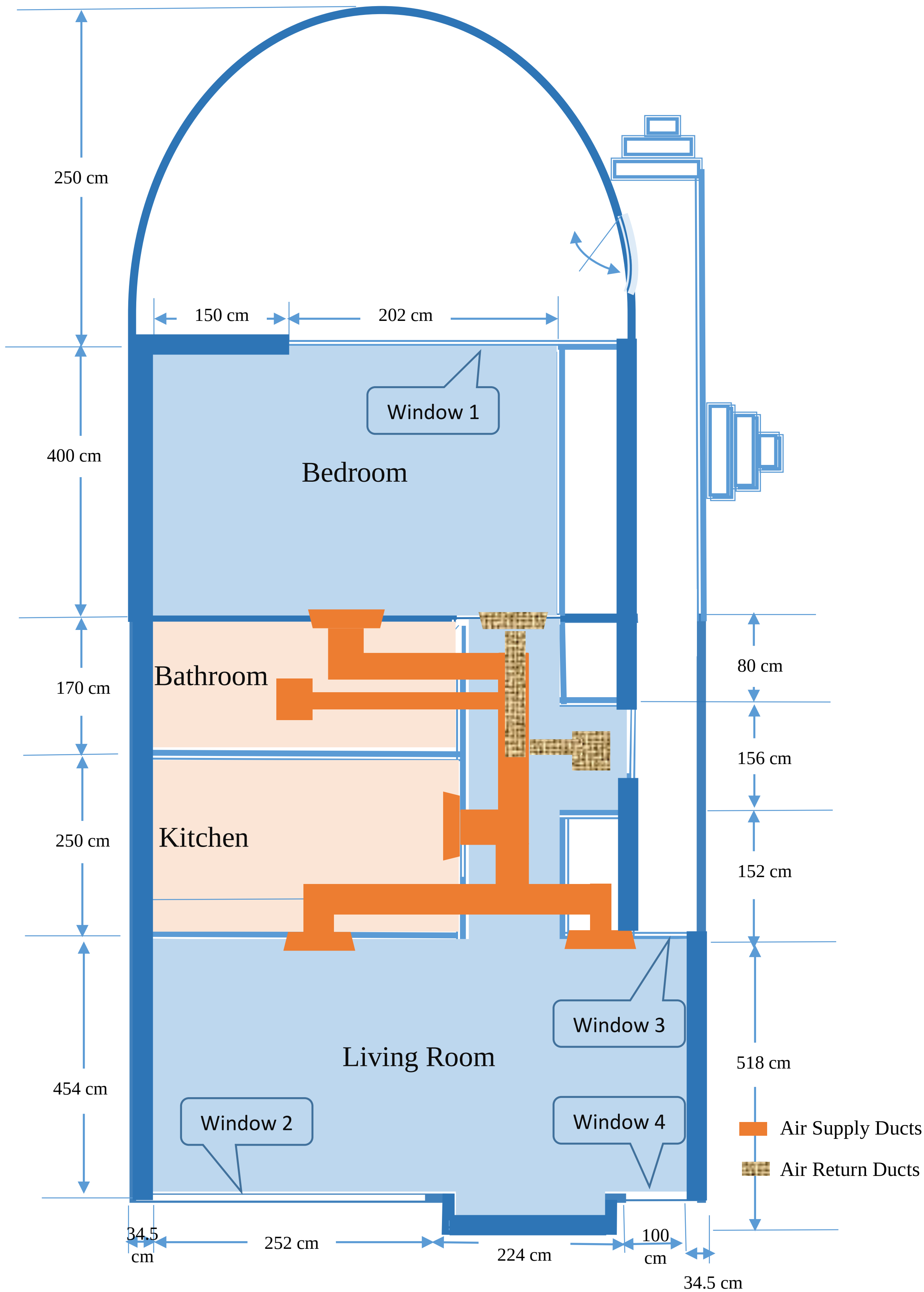


Figure 6.2 Ducts Plan for 3305 and 3307 Houses

1. The refrigerant is a substance that circulates through the air conditioner, alternately absorbing, transporting and releasing heat.
2. A coil is a system of tubing loops through which refrigerant flows and where heat transfer takes place. The tubing may have fins to increase the surface area available for heat exchange.
3. The evaporator is a coil that allows the refrigerant to absorb heat from its surroundings, causing the refrigerant to boil and become a low-temperature vapor.
4. The compressor squeezes the molecules of the refrigerant gas together, increasing the pressure and temperature of the refrigerant.
5. The condenser is a coil that allows the refrigerant gas to give off heat to its surroundings and become a liquid.
6. The expansion device releases the pressure created by the compressor. This causes the temperature to drop and the refrigerant to become a low-temperature vapor/liquid mixture.
7. The plenum is an air compartment that forms part of the system for distributing warmed or cooled air through the house. It is generally a large compartment immediately above the heat exchanger.

1. The ON/OFF cycle HVAC System: The schematic diagram for traditional HVAC system is described figure 6.3. One compressor (comp) and one fan motor (FM) are installed in A/C unit and are applied by three phases line 230 V. They connect to supply by compressor contactor (CC). Blower motor (BM) is connected in three phases 230 V through contactors (BMC). Electronic control board (ECB) is built for detecting and controlling the ON/OFF cycle unit. Thermostat device is connected to ECB to detect the setting and room temperatures. The CC and BMC is controlled by ECB continuously. Transformer 240V/12V is used to apply ECB and relays.

2. The VFD HVAC System: Online block for VFD HVAC system is described in figure 71. The refrigerant cycle (from compressor, condenser, expansion valve and evaporating) is displayed in figure 6.4. Compressor driver "brushless DC compressor driver" is connected between controlling unit and BLDC compressor. Interface unit and thermostat device are joined to controlling unit.

The schematic diagram for VFD HVAC system is explained in figure 6.5. One BLDC compressor (comp) is installed in A/C unit through BLDC compressor driver. The driver is applied by three phases line 230 V. Three phases circuit breaker (CB) is used to protect each compressor and driver. Fan motor (FM) and blower motor (BM) are connected to two phases 230 V through two circuit breakers.

Connected programmable controller (c.pCO) is built for controlling the compressor, fan motor, blower motor and electronic extension valve. The temperature and pressure sensors are fixed on the unit parts and they are connected to c.pCO. Supply air temperature, return air temperature, discharge and suction temperatures, discharge and suction pressure are detected by controlling unit. The VFD HVAC system user interface is the Programmable graphic displays (pGD[1]) terminal that is an electronic device allows graphic management using the icon-based display. The supply c.pCO unit is occurred using a transformer 230V/24V. The compressor driver and c.pCO functions will discuss details in the next section.

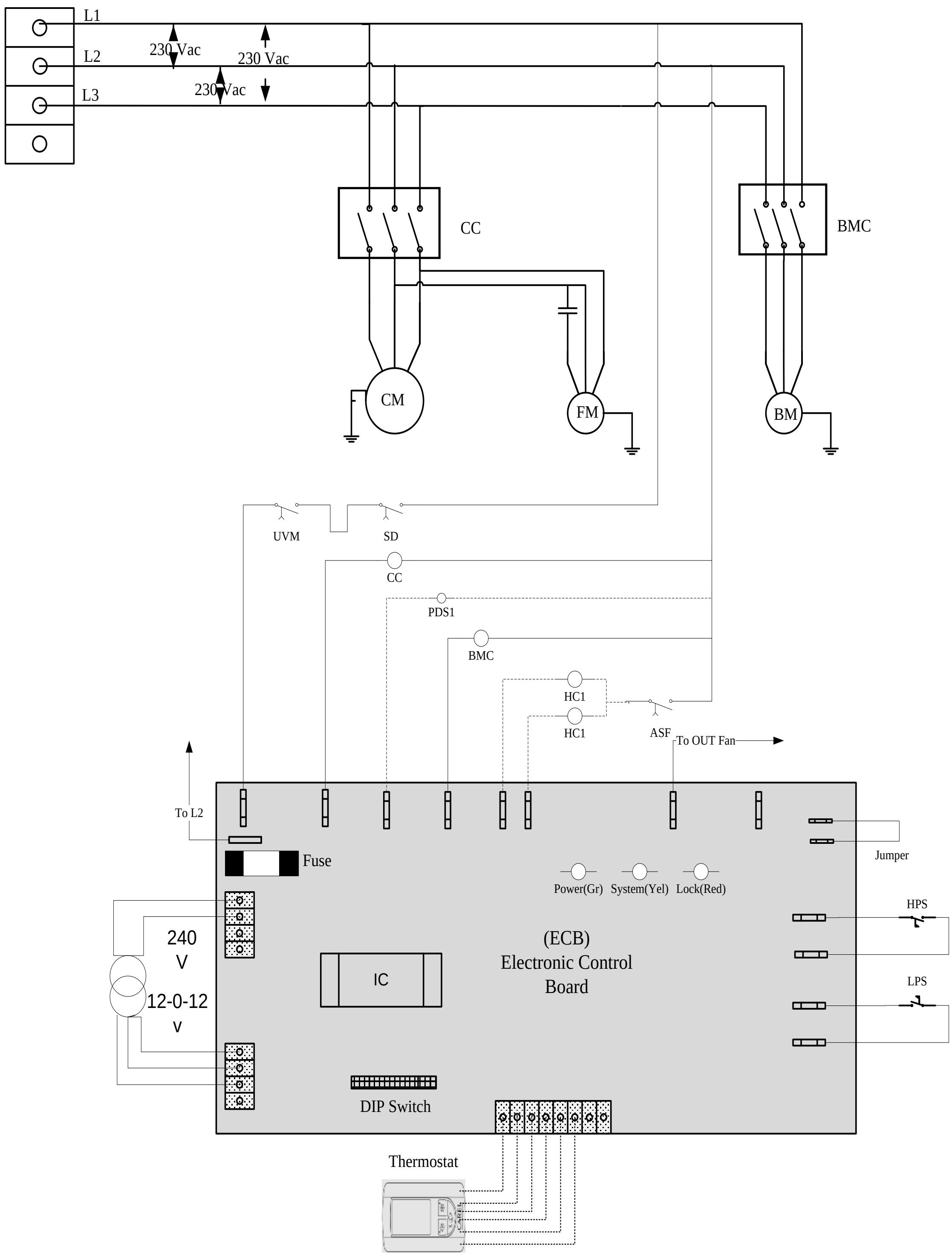


Figure 6.3 The Schematic Diagram for ON/OFF Cycle HVAC System

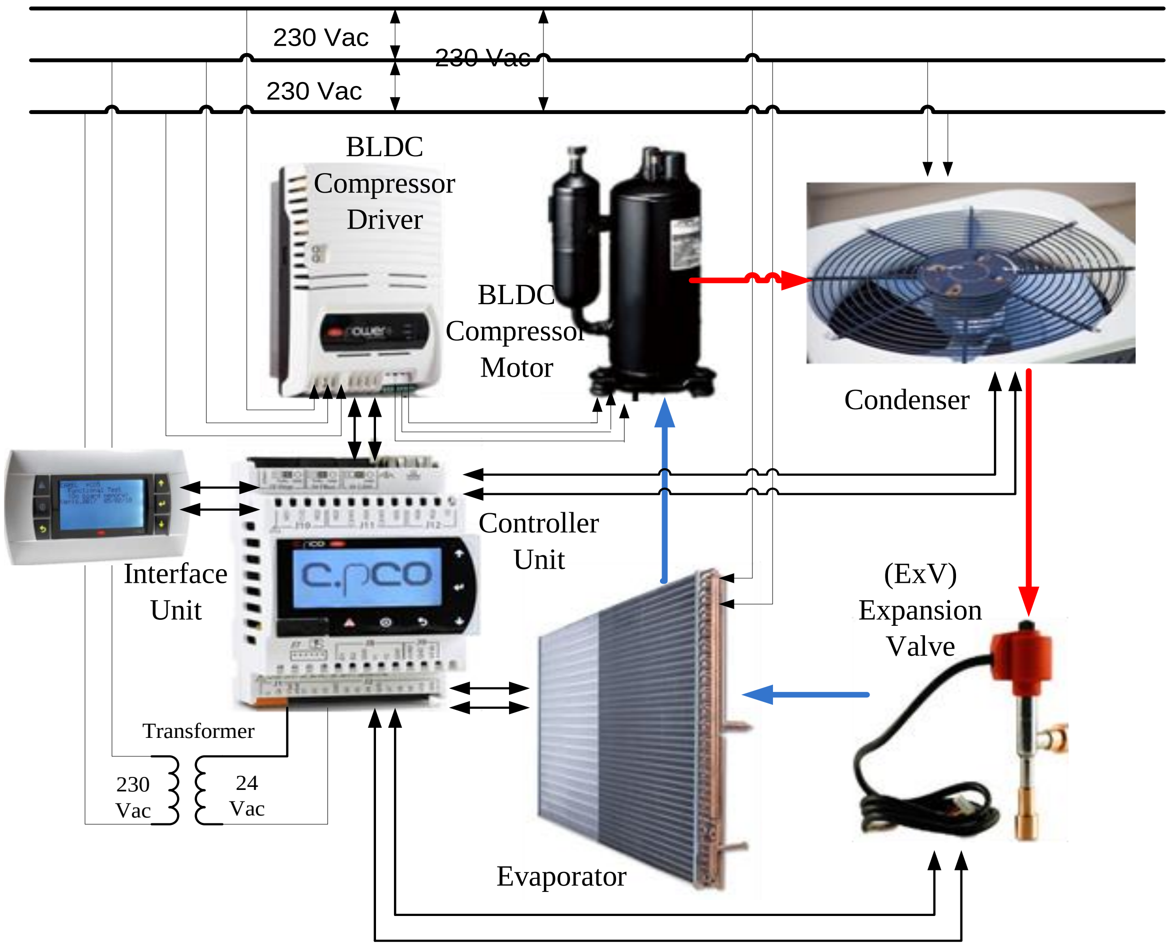


Figure 6.4 Online Diagram for VFD HVAC System

6.1.4 BLDC Compressor Driver

BLDC compressor driver is a special inverter that can control compressors with permanent magnet brushless motors (BLDC/BLAC). The driver is integrated into c.pCO, it brings significant energy savings by modulating compressor speed and consequently the cooling capacity of the unit. Variations in load are managed precisely and with constant control of the compressor envelope.

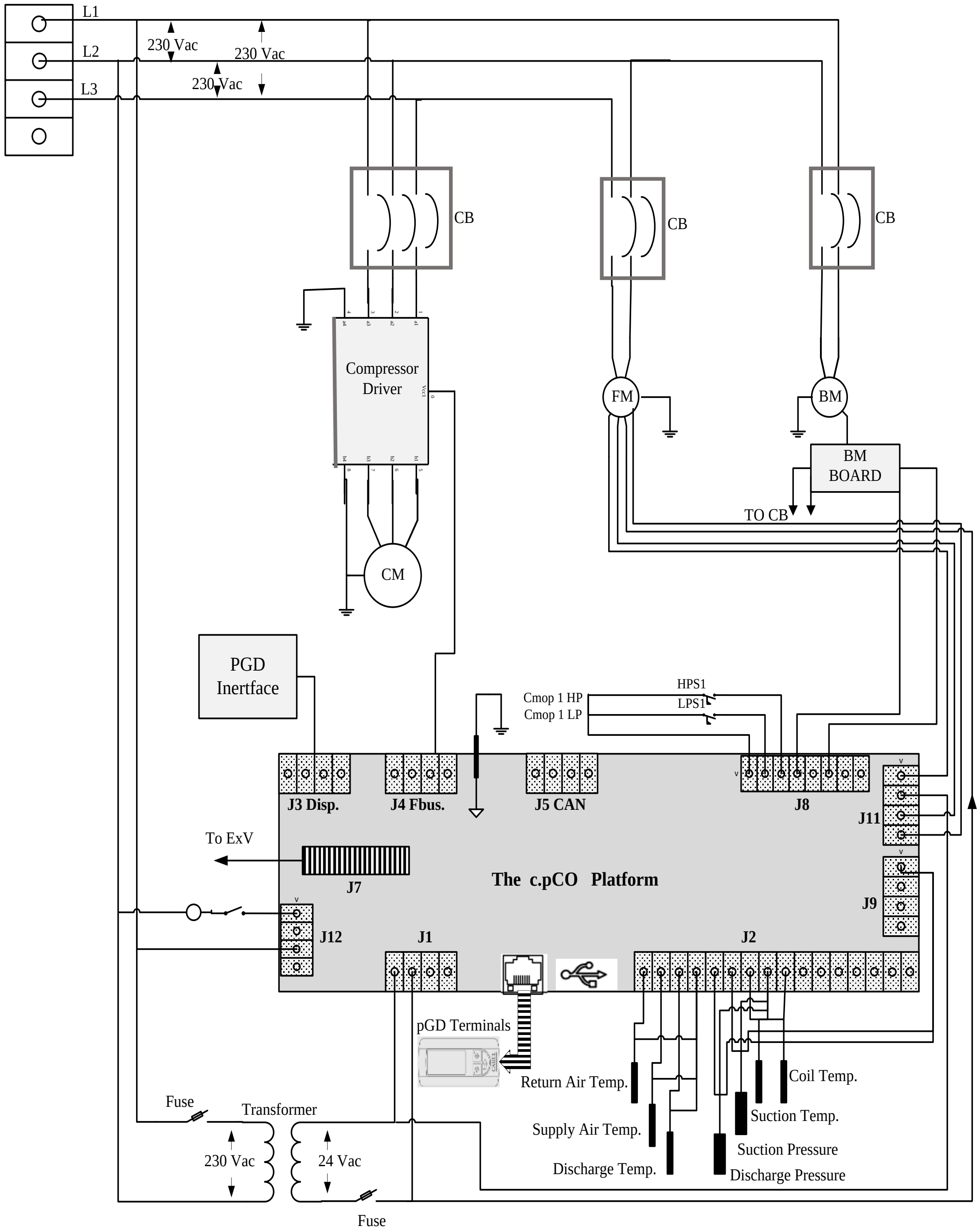


Figure 6.5 The Schematic Diagram for VFD HVAC System

The standard specifications for BLDC compressor driver used in the VFD HVAC system are described in Table 6.2 [42].

Table 6.2 Standard Specification for BLDC Compressor Driver

Inverter type	4THB F010i	
Inverter Control method	Converter	3 Ø Diode Rectifier
	Inverter	3 Ø IPM Inverter
	Method	Sensor-less Vector Control Method
Power Supply	Voltage	3 Ø 200 - 240 V~
	Frequency	50/60 Hz
	Tolerance Voltage	+10/-15% , Frequency ± 5%
PWM Control	Operating Revolution	10 - 130 rps
	Carrier Frequency	4 kHz
	Output Current	34 Arms
Protection	Fin over heat, Over current, Under/over voltage, Overload, Compressor connection loss, Communication loss, PFC converter fault	

The function block diagram of BLDC compressor driver explained in figure 6.6. As we discussed in section 3.6, figure 6.6 shows three main components of VFD, a VFD's rectifier/converter accepts ac line voltage. Then its DC bus stores converted power on capacitor. Finally, it inverter creates desirable frequency/voltage sinusoidal output. Let us look at the driver circuity for the BLDC compressor that takes its supply from a single three-phase power supply 230V - 60 Hz. There are two main sections of operation. The first section consists of a DC rectifier/converter. The DC converter converts the incoming power supply from 3-phase AC to DC using six diodes (Diode Module). DC reactor (Inductors) and capacitors are connected before the converter to reduce the electrical noise being introduced into the power supply due to the switching of the transistors. The second section is the inverter (Power Module) consisting of IGBT transistors. This section generates 3-phase voltage supply to the BLDC compressor motor. The six discrete IGBT transistors are controlled by the c.pCO. The driver has ability to communicate with the Frame Transport Bus for Remote Terminal Unit (FBUS RTU) protocol via the RS485 communication link to c.pCO, which is one of the favorite industrial communications. In this mode, the driver receives frequency and control command from controller unit in order to drive the BLDC compressor.

The software is written in such a way that proper signals are being used to power ON or OFF each transistors at a correct timing depending on the feedback such as the position of the rotors in relation to the stator motor and the voltage levels detected. The BLDC motor of the compressor will receive close to a 3-phase sinusoidal voltage that turns the motor ON. The speed of the motor can be controlled from low to high by varying the frequency/Voltage (power supplied) to the motor through the switching of the transistors. In this way, capacity controlled HVAC can be achieved. When cooling or heating is needed immediately, the motor will turn at the highest speed. When the temperature of the room has stabilized, the motor will turn at a lower speed.

Intelligent Power Modules driving circuit (IPM), detection circuit, overload conditions and other parameters are built in an encapsulated casing. It looks like an integrated circuit except that it is very much bigger in size. The wiring diagram for online BLDC compressor driver is displayed in figure 6.7.

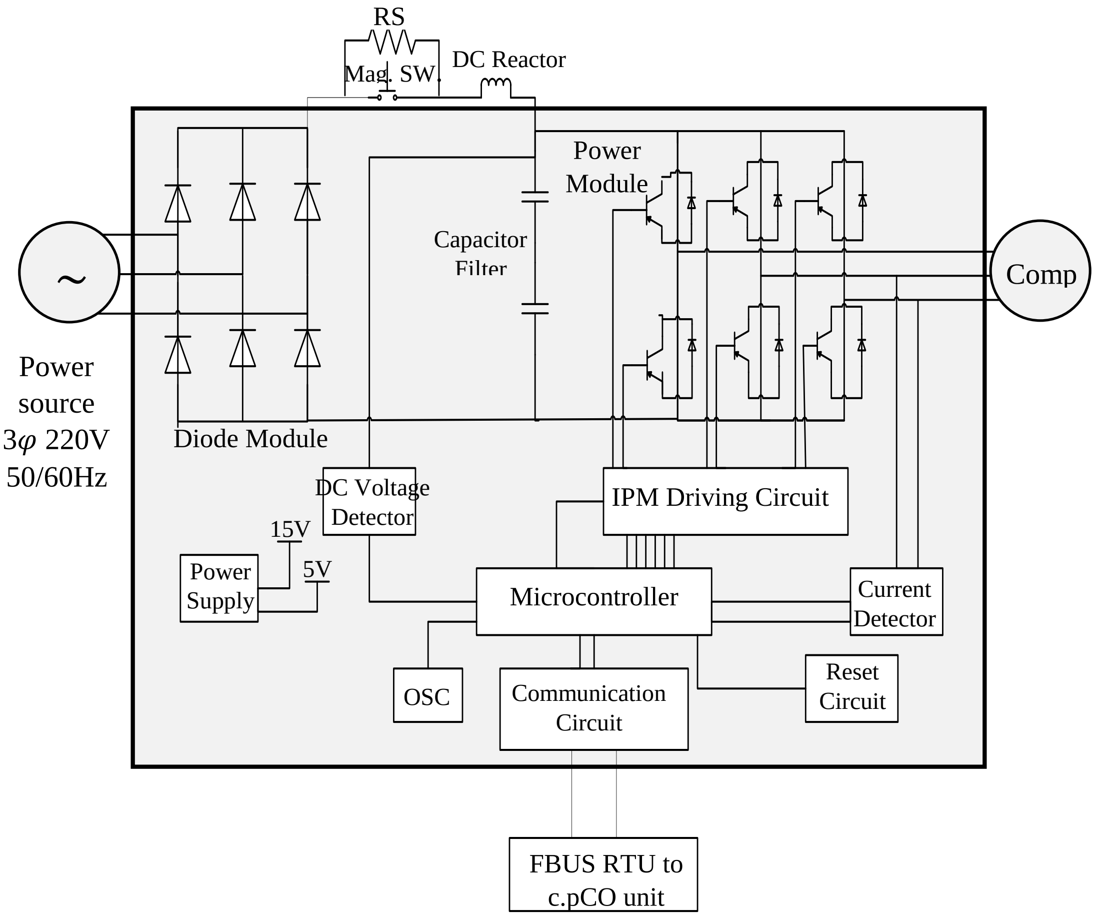


Figure 6.6 The Function Block Diagram of BLDC Compressor Driver

6.1.5 Connected programmable controller (c.pCO) Functions

Microprocessor-based, programmable electronic controller (c.pCO) is a featuring multitasking operating system, compatible with the c.pCO Sistema family of devices, which includes programmable controllers, user terminals, gateways, communication devices and remote management devices. These devices represent a powerful control system that can be easily interfaced with most Building Management Systems (BMS) available on the market. The controller has been developed by manufacturers to provide solutions for several applications in air-conditioning, refrigeration and HVAC system [43]. The c.pCO functions will explain in the follows:

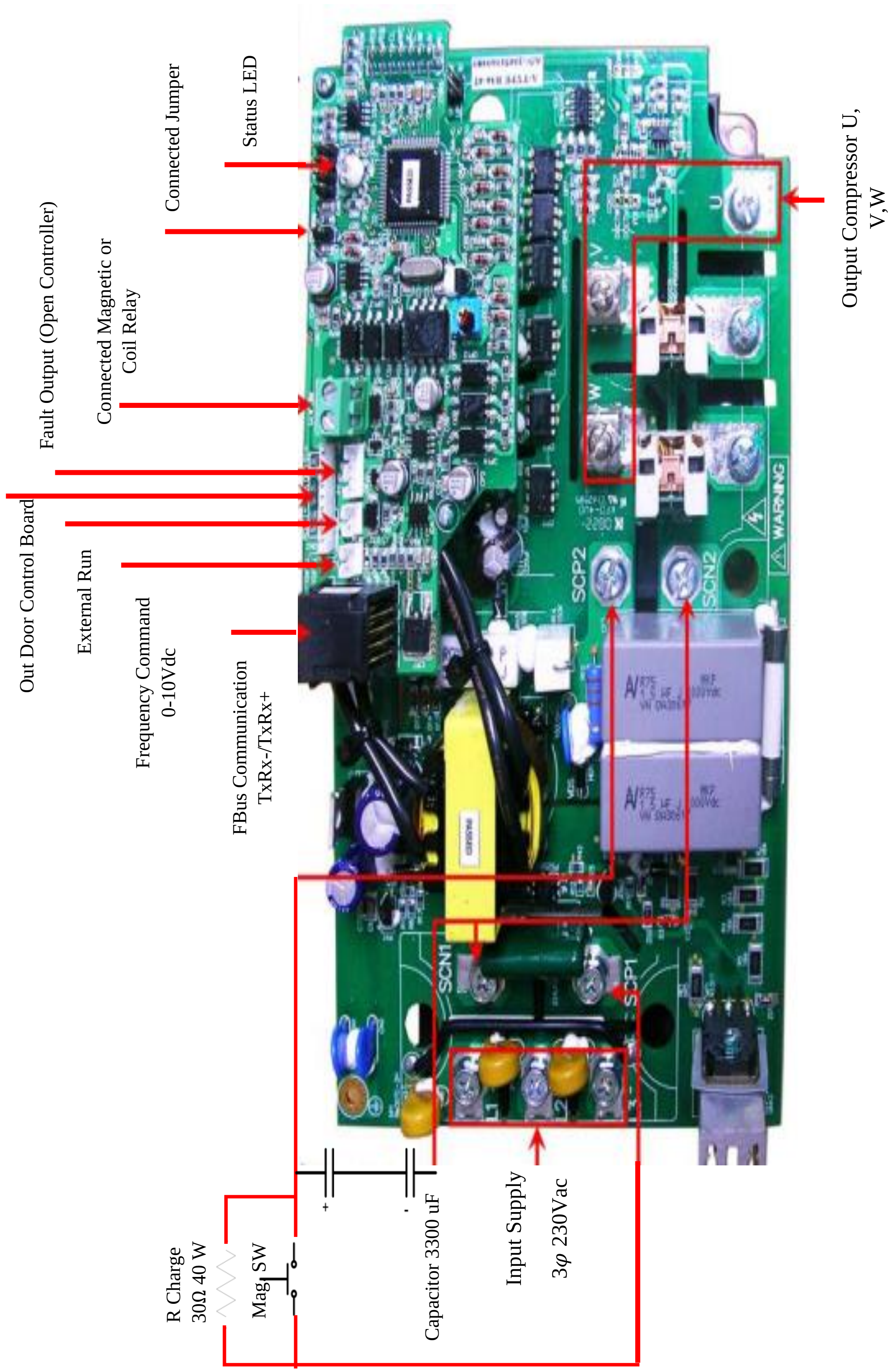


Figure 6.7 The Wiring Diagram of BLDC Compressor Driver

1. Temperature control

The c.pCO unit allows the control of the supply and return temperatures for the unit.

PID Control: There are two types of Proportional, Integral and Derivative (PID) control:

- PID control on startup
- PID control during operation

The startup control must prevent an excess of requested power. Since at startup the status of the load is not known but only the temperature is, the power must be entered little by little, waiting for the reaction of the system. It can regulate on the value of the return temperature using a wide proportional band (2-3 times the nominal thermal gradient) and a large enough integral time that is greater than the system time constant.

2. Evaporator Fan

A delay can be set between the fan startup and thermo-regulation enabling. A delay can also be set between the shutdown of the last compressor and fan shutdown. If on unit shutdown the compressors are off for at least the pump off delay time, then the pump shuts down immediately.

3. Compressors Management

Safety time control: The c.pCO ensures the compressor safety timings as:

- Minimum on time
- Minimum off time
- Minimum time for consecutive startups

These times are in the Compressor menu and can be changed by accessing with Service password.

4. BLDC Regulation

The operating limits (hereafter defined as envelope) of the BLDC compressors are controlled. This control cannot be disabled in order to prevent the compressor from working outside of the safety limits dictated by the manufacturer. All of the compressors inserted thus contain the envelope data.

Besides the operating limits specified by the manufacturer, there is the possibility of customizing the maximum condensation and minimum evaporation thresholds. These thresholds are considered only if they are more restrictive than the operating limits.

The choice of a compressor with a type of gas is binding in the choosing the refrigerant type. The description of the work zones of a generic envelope are shown in figure 6.8:

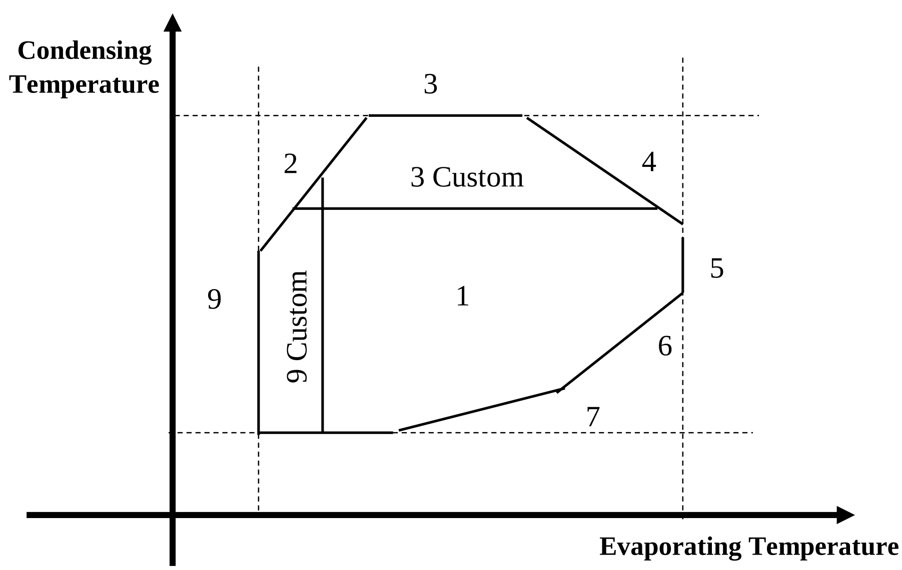


Figure 6.8 The Operation limits for BLDC Compressor Motor

Zone	Description
1	Zone inside the operating limits (the prevention is active to avoid going outside the limits)
2	Max compression ratio
3	Max condensation pressure
3 Custom	Max condensation pressure custom threshold
4	Max motor current
5	Max evaporation pressure
6	Min compression ratio
7	Min differential pressure
8	Min condensation pressure
9	Min evaporation pressure
9 Custom	Min evaporation pressure custom threshold

5. ExV device

The EVD EVO driver for the electronic expansion valve is a fundamental device/control in the c.pCO controller. It allows safe management of the compressor and circuit and reads all of the essential probes for regulating suction superheat, managing the work zone and the discharge temperature.

6. Pump-Down

The purpose of the pump-down function is to reduce the quantity of refrigerant in the evaporator to limit the presence of liquid in suction during the compressor startup phase. Pump-down can be controlled by the electronic expansion valve (ExV). In general, the pump-down can be activated in two phases: at compressor start up or shut down. c.pCO manages the pump-down in both phases. In the compressor shutdown phase it stops when the evaporation pressure reaches the pump-down end set-point. In the compressor startup phase, the pump-down ends when the pressure difference between discharge and suction reaches the nominal value if prevention is enabled or the minimum evaporation pressure threshold is reached.

7. Condenser Fans

Control in chiller mode: Fan control can be modulating or ON-OFF and controls the saturated temperature value equivalent to the condensing pressure. The control diagram is displayed in figure 75 below:

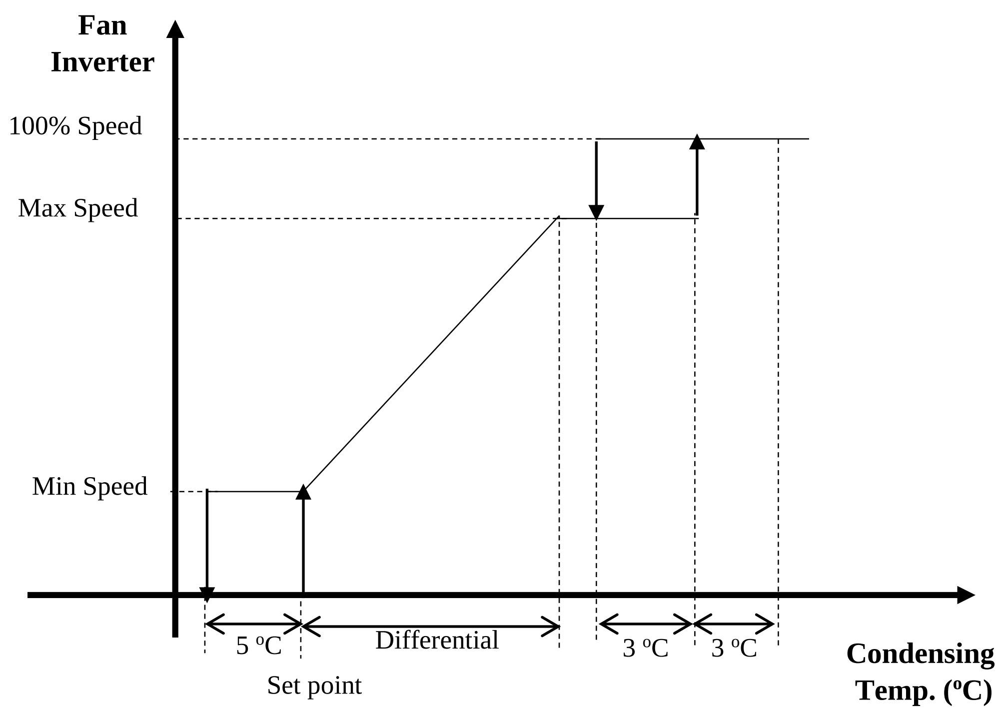


Figure 6.9 The Control Diagram for Fan Motor

In the above figure 6.9, some offsets are given a numeric value, that indicates that they cannot be changed from the display; they are fixed. The fan control set-point is related to the minimum condensation value of the envelope plus an offset.

6.1.6 House, A/C units and Sensors Location

The whole HVAC units are located outdoor on the roof and is linked by duct lines to indoor rooms (figure 6.10). The min-duct air conditioners are designed to facilitate distribution cool air to a house. Three thermocouple sensors are fixed on bedroom, corridor and living room. The temperatures in degree are measured from three position and then we take the average temperature for a house. Airflow sensors are located near inlet air ducts to measure A/C unit flow in kilogram per second. Pressure sensor also placed inside house to measure in house pressure. Thermocouple sensor and Irradiation sensor are placed out house on roof to measure the ambient temperature in degree and daily irradiation in watt per meter square. The sensors location for the temperatures, airflow, pressure, and irradiation are explained in figure 6.10.

6.2 Monitoring and Measurement Systems

In short, monitoring and measurement helps us manage our systems better. The results of monitoring data and other efforts are easier to demonstrate when current and reliable data are available. These data can help us to demonstrate the saving of energy. Figure 6.11 shows the mean parts for monitoring and measurement.

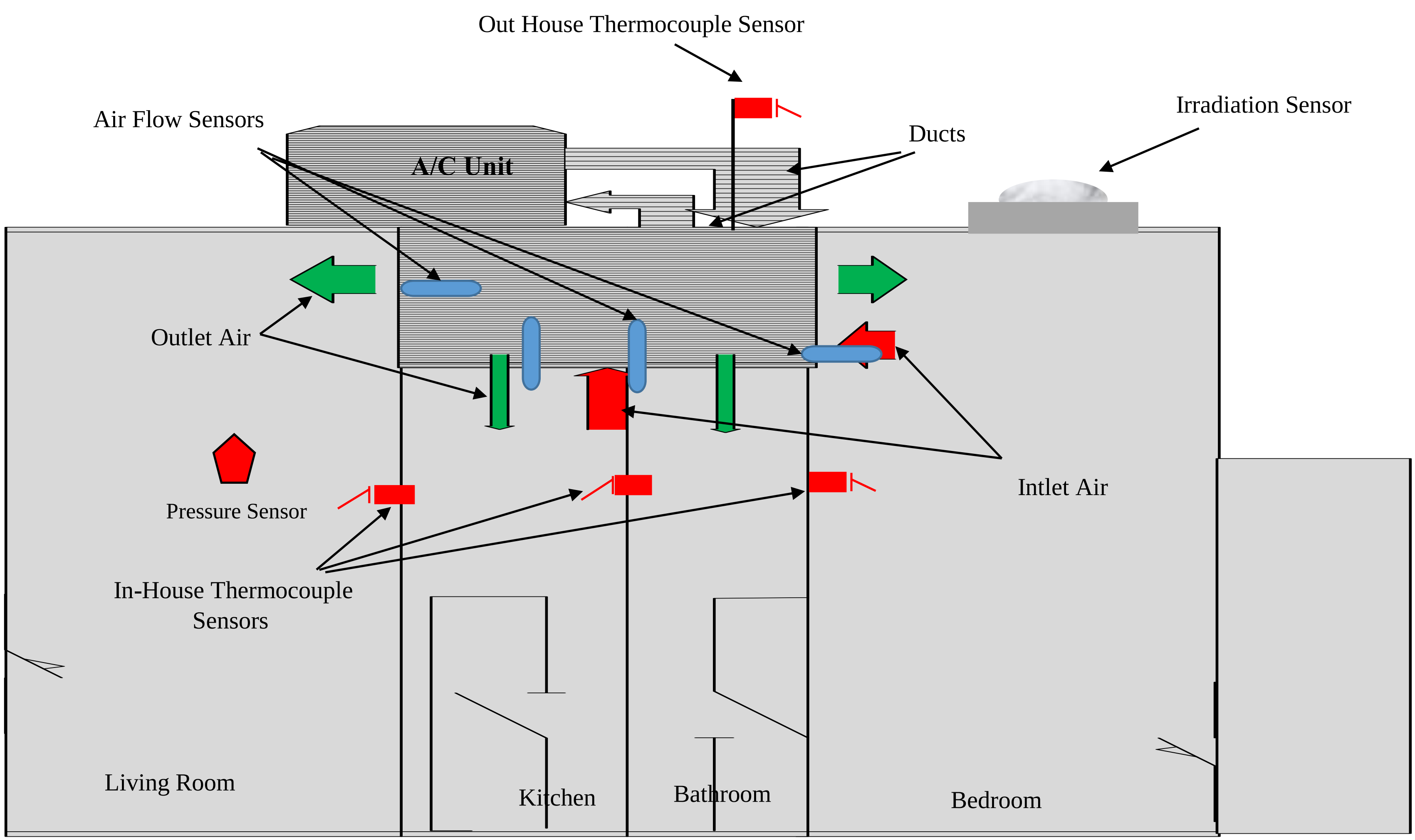


Figure 6.10 Installed A/C Unit with Ducts and Sensors location

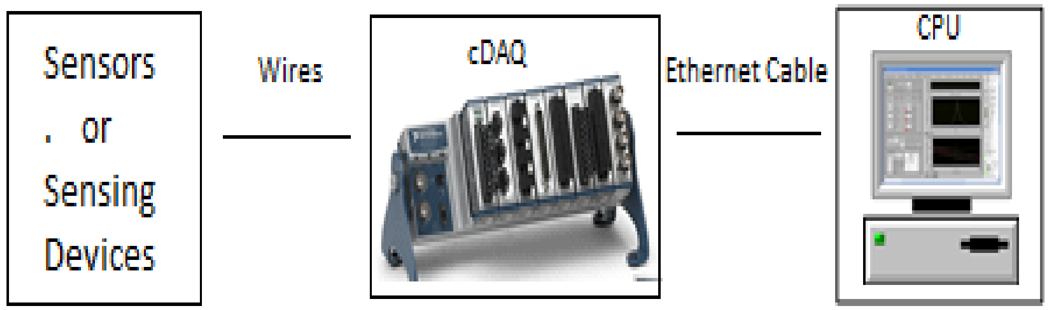


Figure 6.11 Monitoring and Measurement System

Our organization should develop means to:

1. Monitor the three phase voltages and currents, which apply to AC systems from three phase AC source and activities that can have significant environmental impacts and/or compliance consequences. i.e., temperature, humidity, airflow, pressure, wind speed and irradiation. Figure 6.12 shows the block diagram for monitoring and measurement devices. Temperature and humidity are measured in outdoor and indoor and the airflow and pressure only are measured in indoor. The outdoor climate as wind-speed and irradiation also are measured. All measurements are applied using Laboratory Virtual Instrument Engineering Workbench (LabVIEW) program.
2. Track performance Lab VIEW program (including our progress in achieving objectives and targets)
3. Calibrate and maintain monitoring equipment.

LabVIEW is a software program, which is normally taken as an instrument of virtual equipment and automation, is used for system development to measure and analyze the data. In the LabVIEW program setting, the graphic programming has replaced the traditional program writing style and can be derived easy interface to use. Essentially this entire system involves the integration of sensor devices, personal computer (PC) and data acquisition (DAQ) to measure and create a system and to analyze the system. DAQ system has involved physical input/output signals, DAQ device/hardware, driver software and software application. Online HVAC system diagram is provided in figure 79 that illustrates the design method by using LabVIEW software.

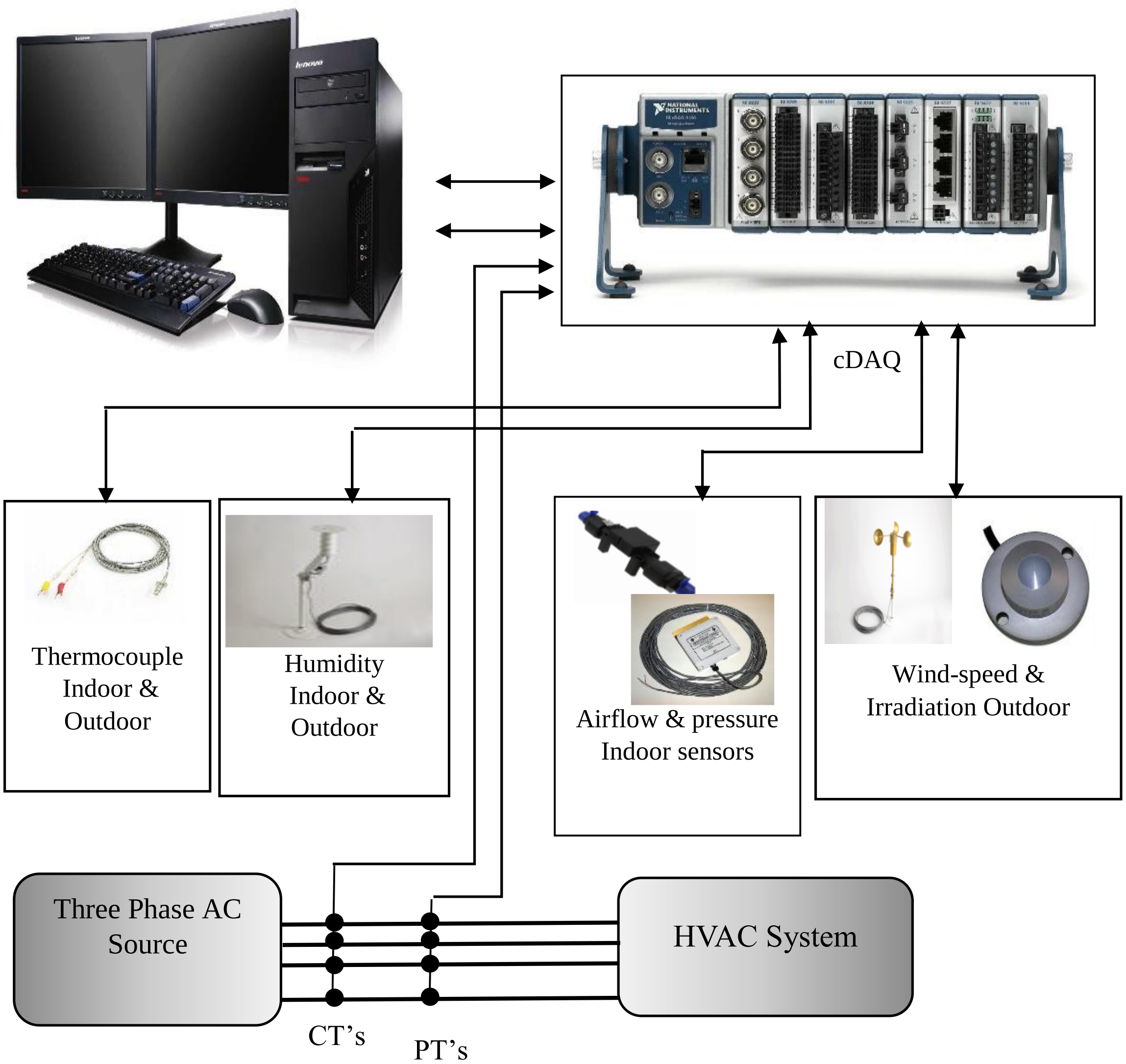


Figure 6.12 HVAC Monitoring and Measurement System

6.2.1 Set-up & Connections

The system is formed by placing and installing the modules on CompactDAQ (cDAQ) chassis and connecting your specific module applications to sensors. NI cDAQ chassis control the data transfer between up to eight NI modules and an external personal computer. Each module contains measurement-specific signal conditioning to connect to an array of sensors and signals and channel-to-channel isolation options, and support for wide temperature ranges to meet a variety of application and environmental needs. A single NI cDAQ Ethernet data acquisition system can manage multiple timing engines to run up to seven separate hardware-timed I/O tasks at different sample rates in the same system. Data Acquisition is the process of acquiring signals from real-world phenomena, digitizing the signals and analyzing, presenting and saving the data.

Hardware setup also requires the connection between cDAQ and CPU local link type configuration through Ethernet cable. For the first time, install your application development environment (LabVIEW) and NI-DAQmx driver. Once the driver of cDAQ chassis is installed on the computer and power source is connected, NI CompactDAQ chassis are automatically detected and configured by NI Measurement & Automation Explorer (MAX). Furthermore, I/O modules are automatically detected by a chassis when they inserted into an available slot, which means the system knows immediately which type of signals the module can measure or generate. Measurement & automation explorer (MAX) software tool is used to configure data acquisition hardware device and the software. This tool creates tasks, channels, scales, interfaces and virtual instruments.

Once MAX software window is opened, expand ‘Devices and Interfaces’ option to confirm your device is detected. The chassis is listed under ‘Devices and Interfaces’ option. To add chassis modules, expand ‘Network Devices’ or right-click it and select ‘Add Device’. Once added, then C Series I/O modules are listed and shown up beneath the chassis automatically as shown in figure 6.13.

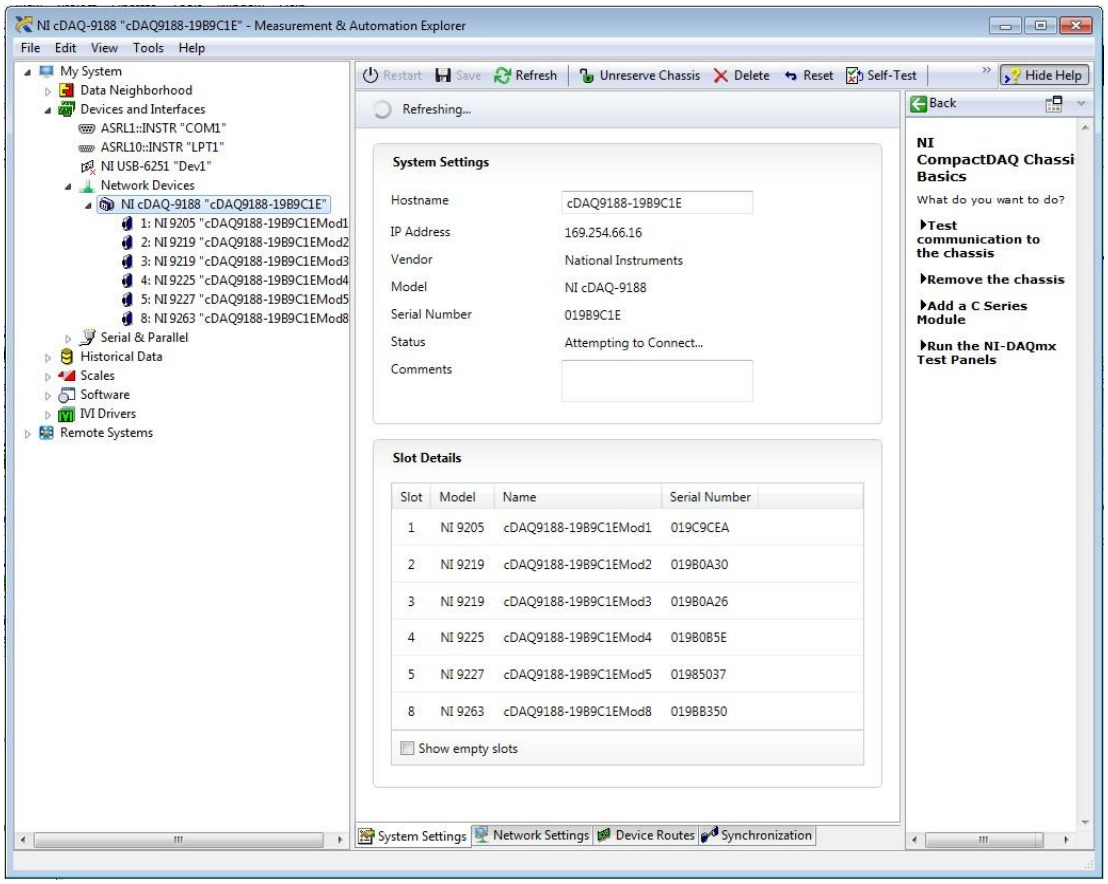


Figure 6.13 MAX Software Window System

6.2.2 System Development and Monitoring

The system measures several physical and electrical characteristics, as well as environmental conditions and storing the result on Excel files that will lead us to evaluate and analyze the data. Data acquisition systems incorporate signals, sensors, actuators, signal conditioning, data acquisition devices, and application software. The purpose of data acquisition is to measure an electrical or physical phenomenon such as voltage, current, temperature, pressure, or speed. PC-based data acquisition uses a combination of modular hardware, application software (LabVIEW), and a computer to take measurements.

LabVIEW programs are called virtual instruments. The front panel is the user interface of the virtual instrument. Front panel with controls and indicators are interactive input and output of the VI means allow an operator to input data into or extract data from a running virtual instrument. Block diagram contains the graphical representation of function to control the objects that appears as terminals. Terminals are the entry and exit ports that exchange information between front panel and block diagram.

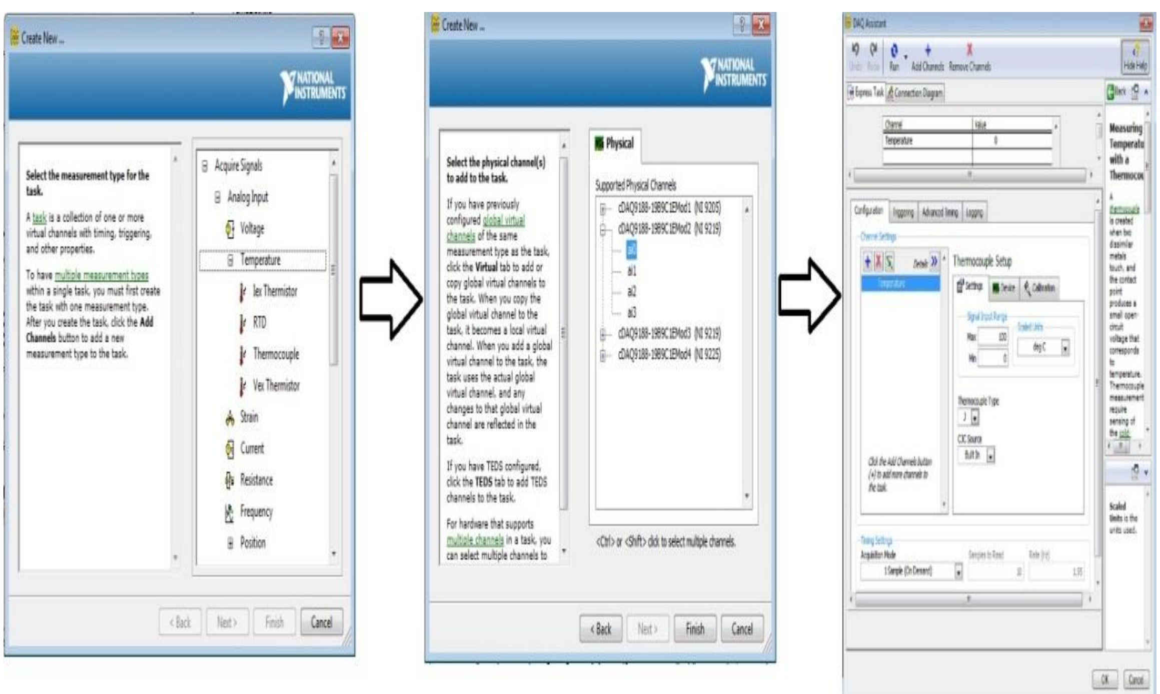


Figure 6.14 cDAQ Software Windows System

On block diagram, dropping and placed a DAQ Assistant block. The DAQ Assistant is a configuration based step-by-step wizard that allows you to set up your measurement. Below figure illustrates the steps to set up DAQ Assistant block. Click on acquire signal, analog input, temperature and then select thermocouple for measuring temperature. Next, choose a channel 'AI 0' where thermocouple is connected to module 9219. Click finish, DAQ Assistant will present a series of options that can use to further configure and customize the measurement. Click OK button, the DAQ Assistant automatically generate the code in the background. Select the chart and connect the two together for data transfer. The data is visualized on the front panel. Similar procedures are applied to add all electrical and environmental parameters measurement.

After getting the voltage and current, we multiply the current and the voltage to calculate the power. Later calculations will allow us to arrange the data in an array, showing the data in the table, storing the data on the files and the plotting of parameters, such as the RMS voltages, RMS currents, solar irradiation, power, temperature, wind speed, pressure, …etc. that are also monitored on front panel through graphical representation on LabVIEW.

Data received from the cDAQ device needs to be processed for display and storage. A module is developed to arrange the entire data in an array and in a table for online continuous reading and monitoring and then saved to an excel file. The data is displayed as tables for ON/OFF unit as following: figure 6.15.a shows the date, time, four temperatures for inside and outside air temperatures (C^{o}), solar irradiation (W/m^2), pressure (Hg) and three air flow (kg/h) tables. Figure 6.15.b shows RMS voltages (V), RMS currents (A), and phase angle tables. The Storage Data for segregated and aggregate active and reactive power from cDAQ devices by LabVIEW program, are presented in figure 6.15.c.

Environmental Parameters

Date	Time	T1 (C)	T2 (C)	T3 (C)	T (Avrage House Air) (C)	Tout (C)	Irra (W/m2)	Air flow 1 (kg/h)	Air flow 2 (kg/h)	Total Air flow (kg/h)	Pressure Hg
27-01-2016	00:52:34	21.941151	22.436076	21.265382	21.880869	16.431776	13.233459	2536.571881	1059.301283	3595.873164	27.207037
27-01-2016	00:52:44	21.812409	22.240938	21.112627	21.721991	16.532079	13.230241	2536.800330	1059.247665	3596.047995	27.210256
27-01-2016	00:52:54	21.728453	22.079471	20.927300	21.578408	16.383622	13.234890	2537.620058	1059.375327	3596.995386	27.192489
27-01-2016	00:53:04	21.688292	21.942586	20.721995	21.450958	16.418307	13.244904	2538.664876	1059.219579	3597.884455	27.183305
27-01-2016	00:53:14	21.593688	21.836130	20.668614	21.366144	16.367732	13.232744	2532.117125	1058.078275	3590.195400	27.155152
27-01-2016	00:53:24	21.470885	21.670209	20.443618	21.194904	16.269841	13.231671	2533.746504	1058.808505	3592.555010	27.139274
27-01-2016	00:53:34	21.376994	21.559288	20.254907	21.063730	16.273324	13.231314	2531.586317	1058.203384	3589.789701	27.139617
27-01-2016	00:53:44	21.292435	21.445401	20.092157	20.943331	16.186572	13.235963	2529.842712	1056.919097	3586.761810	27.148114
27-01-2016	00:53:54	21.273261	21.411465	20.019025	20.901250	16.159144	13.233102	2533.471022	1057.953165	3591.424187	27.153908
27-01-2016	00:54:04	21.154029	21.433475	19.822142	20.803216	16.223828	13.228095	2533.403831	1058.147212	3591.551043	27.159573
27-01-2016	00:54:14	21.036925	21.399786	19.722047	20.719586	16.193736	13.232387	2530.685959	1056.717390	3587.403349	27.162405
27-01-2016	00:54:24	20.956451	21.388128	19.565898	20.636826	16.242315	13.240254	2538.765663	1059.370221	3598.135883	27.165409
27-01-2016	00:54:34	20.904504	21.267580	19.463793	20.545293	16.308288	13.230956	2538.644719	1059.150641	3597.795360	27.180086
27-01-2016	00:54:44	20.786945	21.129149	19.366757	20.427617	16.272942	13.232387	2537.720845	1059.074043	3596.794888	27.175709
27-01-2016	00:54:54	20.691267	20.956910	19.219914	20.289364	16.349949	13.240612	2535.352367	1058.504668	3593.857035	27.180043
27-01-2016	00:55:04	20.623385	20.834246	19.090702	20.182778	16.400310	13.229168	2532.742000	1056.977822	3589.719823	27.182876
27-01-2016	00:55:14	20.548363	20.849801	18.943629	20.113931	16.272577	13.232744	2531.593036	1058.216150	3589.809186	27.184464

Figure 6.15 Storage Data from cDAQ Devices by LabVIEW Program for ON/OFF Unit

(a) Online Data Date, Time, Four Temperatures, Solar Irradiation, Pressure and Three Air Flow Tables.

(Voltage & Current) RMS, PF

Date	Time	V1 RMS (V)	V2 RMS (V)	V3 RMS (V)	I1 RMS (A)	I2 RMS (A)	I3 RMS (A)	PF1	PF2	PF3
27-01-2016	00:52:36	122.887502	122.732459	122.835752	3.190629	0.155445	3.144999	0.611424	0.809277	0.994444
27-01-2016	00:52:46	123.187903	123.225512	122.575578	3.189136	0.155966	3.144380	0.609529	0.815225	0.994335
27-01-2016	00:52:56	123.969938	121.977726	122.926173	3.203853	0.155385	3.157111	0.613339	0.808455	0.994894
27-01-2016	00:53:06	123.472915	122.150821	123.171522	3.189562	0.155377	3.143047	0.617951	0.807341	0.994351
27-01-2016	00:53:16	123.819316	123.056528	121.976265	3.179390	0.156632	3.134324	0.608000	0.814651	0.994392
27-01-2016	00:53:26	123.046014	123.009006	122.623220	3.192692	0.155265	3.147714	0.610751	0.812776	0.994334
27-01-2016	00:53:36	124.295921	122.125584	122.259621	3.194517	0.156425	3.145664	0.623152	0.811351	0.994010
27-01-2016	00:53:46	122.425968	122.040164	122.130837	15.605386	14.208817	17.026672	0.835182	0.911781	0.906992
27-01-2016	00:53:56	123.131666	122.984164	121.592682	15.756223	14.549522	17.172794	0.842570	0.918770	0.909660
27-01-2016	00:54:06	123.886558	122.435006	121.436122	16.214840	14.805242	17.389408	0.844007	0.914477	0.907832
27-01-2016	00:54:16	123.466236	122.767184	121.437126	16.038926	14.720719	17.381592	0.848032	0.921942	0.913726
27-01-2016	00:54:26	122.749378	122.791099	122.075789	16.197767	14.779677	17.618290	0.846697	0.920742	0.916147
27-01-2016	00:54:36	123.967888	122.154526	121.562700	16.348985	14.876793	17.514388	0.852146	0.920048	0.914038
27-01-2016	00:54:46	124.029101	122.114142	121.748274	16.387666	14.847110	17.469514	0.853997	0.919239	0.915408
27-01-2016	00:54:56	122.948987	122.893471	122.000066	16.328252	14.888849	17.717723	0.844566	0.918840	0.914333
27-01-2016	00:55:06	122.892915	122.822323	122.232693	16.280715	14.818480	17.704868	0.842525	0.917819	0.913413
27-01-2016	00:55:16	123.399024	121.891988	122.574716	16.313801	14.672578	17.523632	0.851029	0.918213	0.916627

Figure 6.15 Storage Data from cDAQ Devices by LabVIEW Program for ON/OFF Unit

(b) Online Data RMS Voltages, RMS Currents, and Phase Angle

P (Watt), Q (VAR)

Date	Time	P1 (W)	P1 (W)	P1 (W)	P(Totral) (W)	Q1 (VAR)	Q1 (VAR)	Q1 (VAR)	Q (Total) (VAR)
27-01-2016	00:52:36	239.732276	15.439513	384.171923	639.343713	310.260815	11.207045	40.666570	362.134430
27-01-2016	00:52:46	239.461245	15.667826	383.240647	638.369718	311.447649	11.130583	40.968415	363.546647
27-01-2016	00:52:56	243.606957	15.323108	386.109792	645.039856	313.701784	11.155273	39.169845	364.026902
27-01-2016	00:53:06	243.364274	15.322855	384.947117	643.634246	309.631427	11.199461	41.090124	361.921012
27-01-2016	00:53:16	239.351209	15.702044	380.169105	635.222358	312.549172	11.178312	40.432824	364.160308
27-01-2016	00:53:26	239.932327	15.523220	383.795817	639.251364	311.065969	11.126635	41.031118	363.223722
27-01-2016	00:53:36	247.432177	15.499654	382.284146	645.215977	310.545204	11.167117	42.029616	363.741937
27-01-2016	00:53:46	1595.619612	1581.070368	1886.074023	5062.764003	1050.726269	712.132878	875.767515	2638.626662
27-01-2016	00:53:56	1634.660695	1644.011029	1899.448349	5178.120073	1044.908391	706.427426	867.294391	2618.630208
27-01-2016	00:54:06	1695.441414	1657.654153	1917.070982	5270.166550	1077.385036	733.478800	885.508635	2696.372471
27-01-2016	00:54:16	1679.328772	1666.153787	1928.665199	5274.147758	1049.432033	699.985612	857.672904	2607.090550
27-01-2016	00:54:26	1683.457993	1670.975035	1970.417762	5324.850789	1057.908458	708.087454	862.119948	2628.115860
27-01-2016	00:54:36	1727.085903	1671.973571	1946.074607	5345.134080	1060.606596	712.015334	863.623087	2636.245016
27-01-2016	00:54:46	1735.788452	1666.618933	1946.965945	5349.373329	1057.491268	713.794669	856.128238	2627.414175
27-01-2016	00:54:56	1695.502270	1681.239866	1976.388095	5353.130232	1074.940463	722.073045	875.354992	2672.368501
27-01-2016	00:55:06	1685.710037	1670.468244	1976.730541	5332.908821	1077.738580	722.552509	880.865843	2681.156932

Figure 6.15 Storage Data from cDAQ Devices by LabVIEW Program for ON/OFF Unit

(c) Online Data The segregated and aggregate active and reactive power

Figures 6.16 (a, b, c) display the instantaneous values (peak to peak) of line voltage and current with corresponding RMS values. The super imposed graph is displayed in figure 6.17 that shows the instantaneous values for four temperatures and pressure with time.

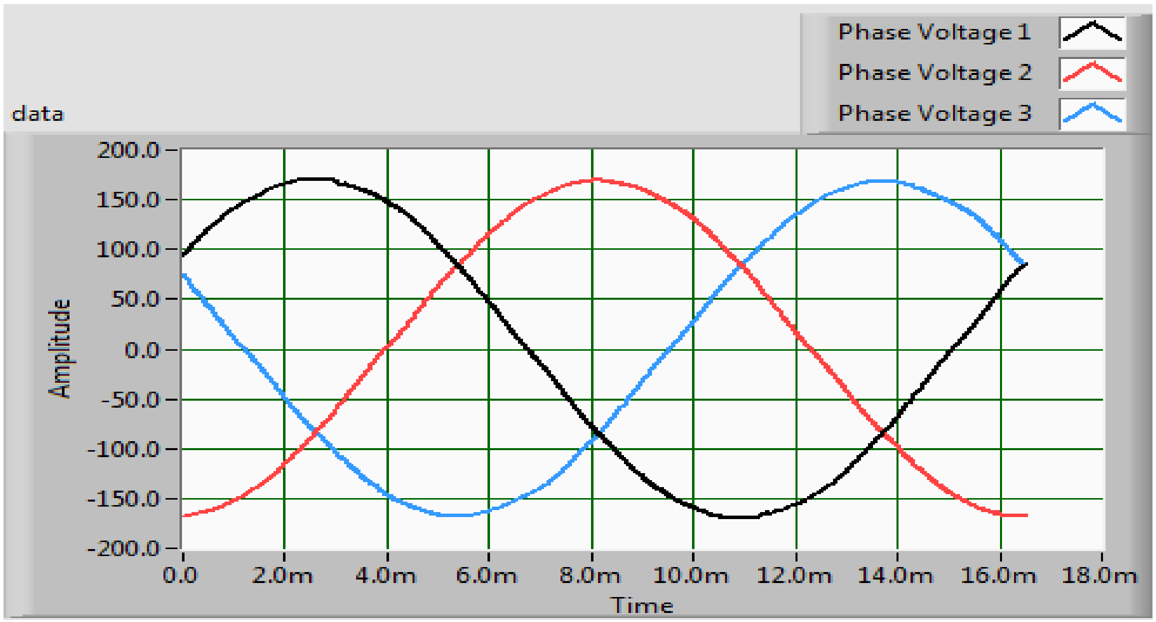


Figure 6.16.a Online Peak to Peak and RMS Three Phase Voltages for ON/OFF Unit

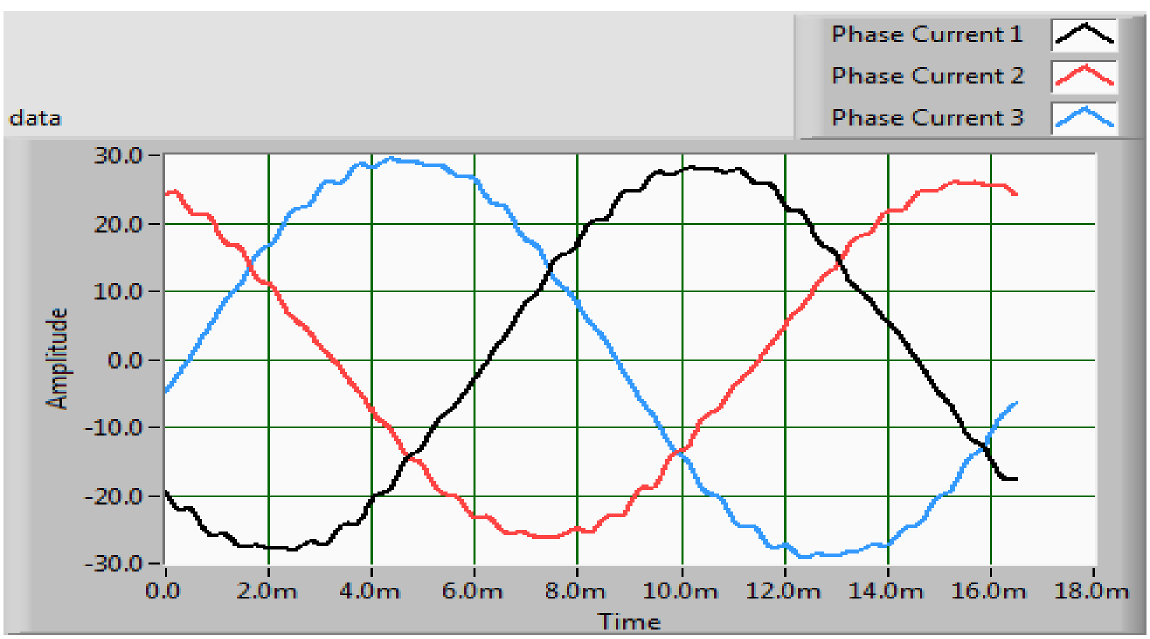


Figure 6.16.b: Online Peak to Peak and RMS Three Phase Currents for ON/OFF Unit

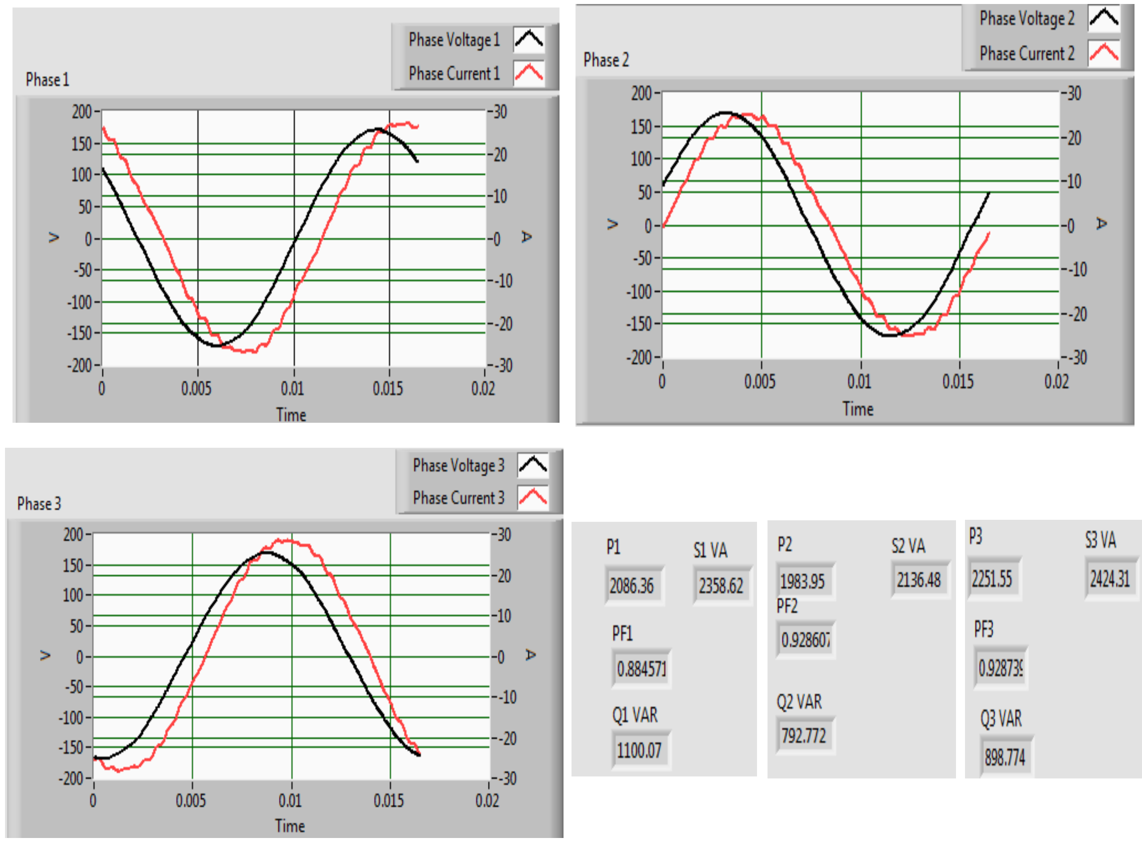


Figure 6.16.c Online Peak to Peak and RMS Three Phase Voltages and Currents Individually with Power Factor, Active and Reactive power

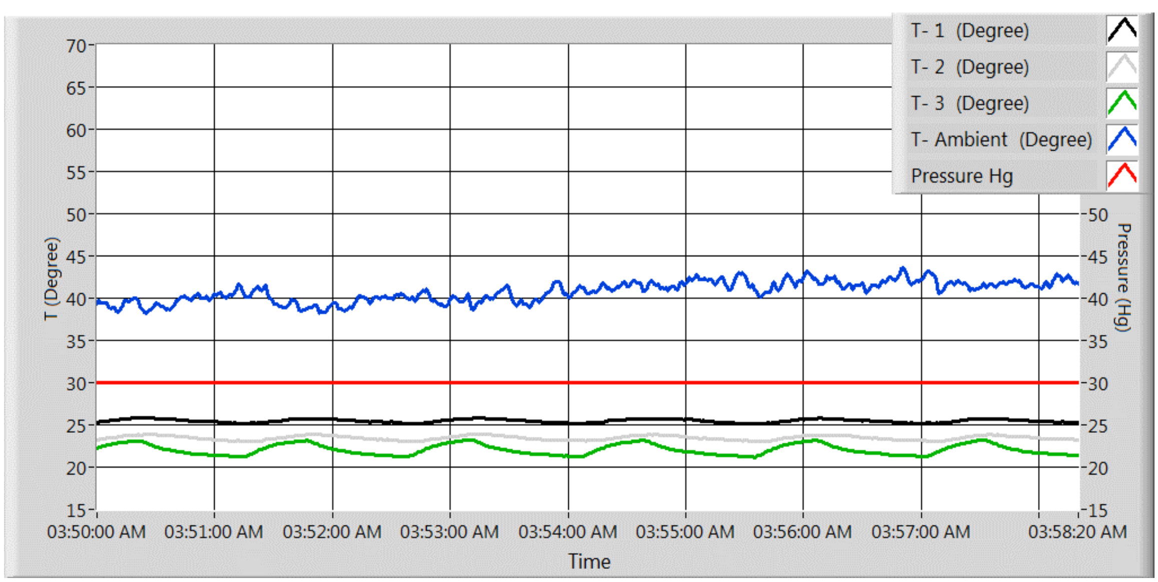
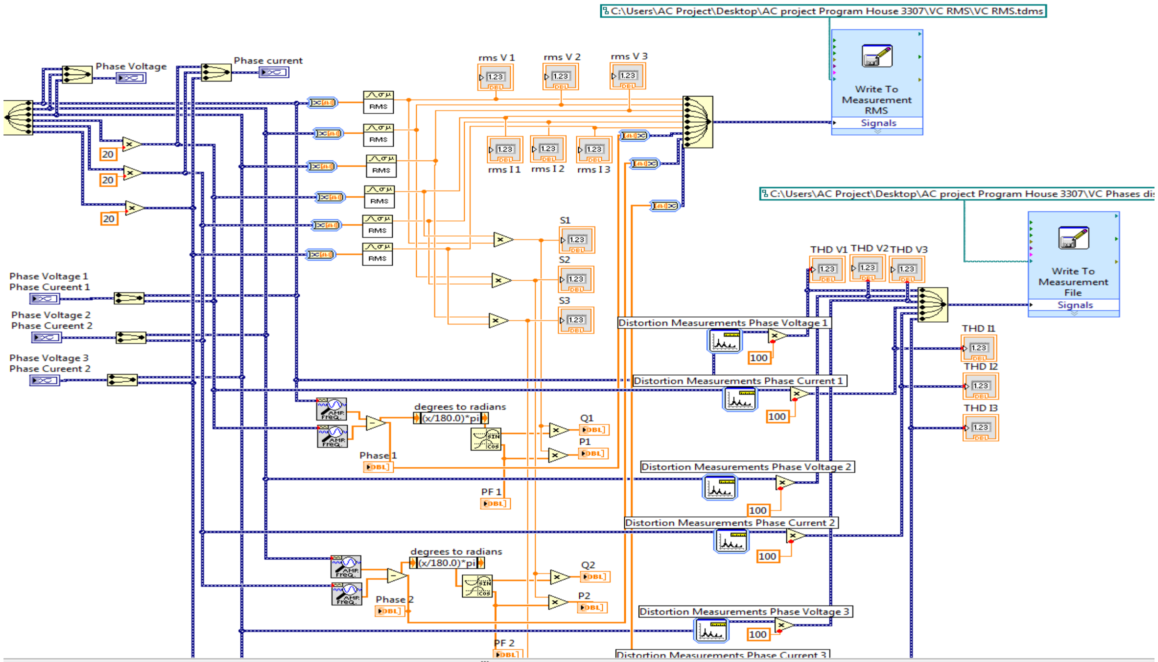


Figure 6.17 Online Instantaneous Values for Four Temperatures and Pressure with Time.

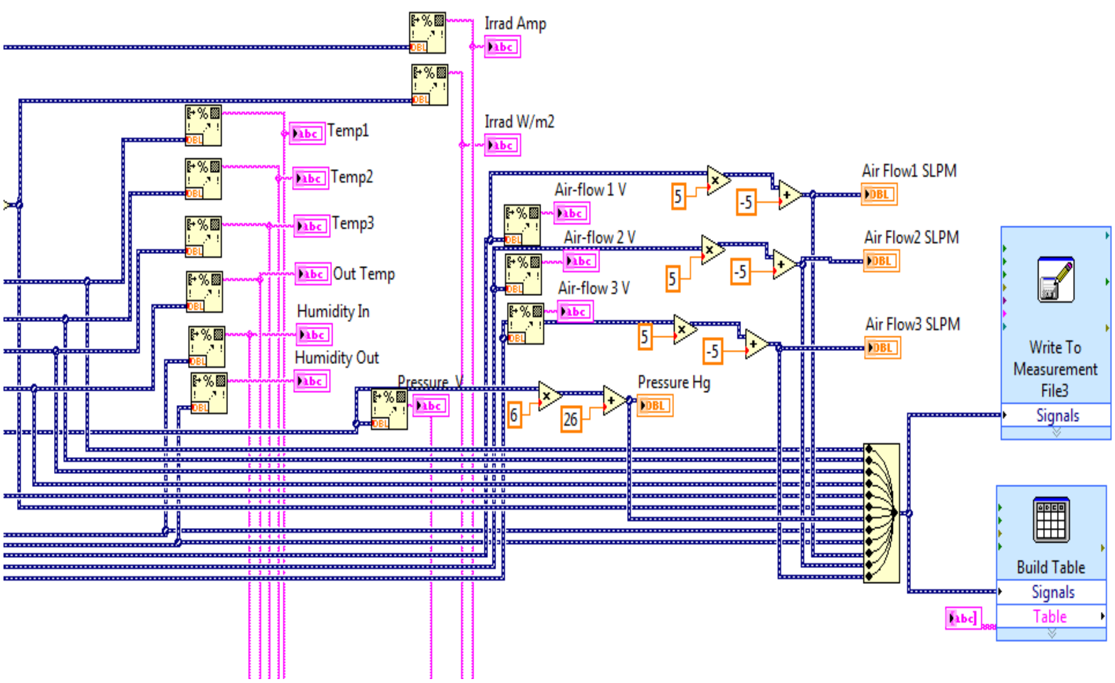
NI LabVIEW software is used for a wide variety of applications and industries, which can make it challenging to answer the question: “What is LabVIEW?” LabVIEW is a highly productive development environment for creating custom applications that interact with real-world data or signals in fields such as science and engineering.

The net result of using a tool such as LabVIEW is that higher quality projects can be completed in less time with fewer people involved. Across different industries, the tools and components they need to succeed vary widely, and it can be a daunting challenge to find and use all these disparate items together. LabVIEW is unique because it makes this wide variety of tools available in a single environment, ensuring that compatibility is as simple as drawing wires between functions.

Figure 6.18 shows the block diagram LabVIEW data processing path coming from the data acquisition system through the cDAQ Assistant. The VI allows to setup different channels for parameters with scaling factor and corresponding calibration of each channel. The instantaneous values of all variables like voltages, currents and irradiation could then be processed, analyzed, used for online control, online display and storage. Figure 6.18.a shows the developed module for taking a mean value of a certain specified time interval for any a voltage and current signals. The figure shows the developed graphical programming block diagram to measure and monitor the RMS values for voltage and current supply and the power factor. The values are used to calculate consume active and reactive power for AC unit. Figure 6.18.b shows the developed graphical programming block diagram, which is used to measure and monitor the environmental parameters such as temperature for out and inside house, air flow for AC unit, in house pressure, out and in house humidity and irradiance.



(a)



(b)

Figure 6.18 Developed program for

(a) RMS Voltage and Current

(b) Environmental parameters

The front panel of the developed virtual instrument depicts graphics and numerical data of all parameters and variables. The data are stored in the measurement file and in Excel format. All stored information is based on instantaneous and mean values. Figures 6.19 (a, b, and c) display the RMS voltage and current values, power factor for three phase, active and reactive power, and the environmental parameters as Excel sheets.

Date	Time	V1 (RMS) Volt.	V2 (RMS) Volt.	V3 (RMS) Volt.	I1 (RMS) Amp.	I2 (RMS) Amp.	I3 (RMS) Amp.	PF1	PF2	PF3
27-01-2016	00:52:36	125.3174198	125.1810883	123.9258872	24.18580837	21.74305508	26.48530338	0.455813849	0.514376238	0.509502169
27-01-2016	00:52:46	125.6889653	123.8800937	124.6747001	24.36574136	21.50765243	26.36793468	0.461545821	0.51414293	0.512093035
27-01-2016	00:52:56	126.133246	124.5578877	123.6408875	24.311546	21.68152064	26.23582911	0.460462835	0.514460598	0.510487192
27-01-2016	00:53:06	126.164875	124.585773	123.7647706	24.30896524	21.72720716	26.3642178	0.459049814	0.514687127	0.509481197
27-01-2016	00:53:16	125.1040178	124.5485801	124.8045781	24.27659747	21.41818671	26.47167515	0.459339063	0.515145491	0.513852099
27-01-2016	00:53:26	125.7500583	125.0230743	123.6848514	24.15897786	21.6760972	26.29713593	0.455725992	0.513253688	0.508329307
27-01-2016	00:53:36	125.388554	125.3238904	123.9037853	24.09654541	21.50484982	26.31153522	0.457074403	0.515535759	0.511529637
27-01-2016	00:53:46	125.8262837	124.0791404	124.6758624	24.37336275	21.42889778	26.31845636	0.456625017	0.510534334	0.508647774
27-01-2016	00:53:56	125.3592474	124.3051522	124.9163851	24.12918859	21.21872189	26.20092454	0.45950256	0.51384528	0.512520857
27-01-2016	00:54:06	126.1219545	124.6331786	123.8615143	24.21379328	21.47572422	26.2324849	0.456748014	0.513600026	0.508969248
27-01-2016	00:54:16	125.5300239	125.2326007	123.8171767	24.1639081	21.5616754	26.354898	0.455411295	0.514393484	0.509906185
27-01-2016	00:54:26	125.5762816	125.2540358	123.8365091	24.12370114	21.51608579	26.32469924	0.454649686	0.514143501	0.509511947
27-01-2016	00:54:36	126.1146201	124.708102	123.78355	24.15242207	21.47636247	26.11501806	0.459005522	0.514409038	0.510076109
27-01-2016	00:54:46	125.6756323	125.1608173	123.6810856	24.1791247	21.43279201	26.26337387	0.454781142	0.513839647	0.510264511
27-01-2016	00:54:56	125.5525294	124.1889825	124.9058817	24.47590187	21.26299179	26.34758331	0.456448605	0.510469897	0.511437328
27-01-2016	00:55:06	125.6370843	124.0885351	124.8162516	24.20682779	21.04877997	26.08435493	0.459364739	0.513157784	0.513348516
27-01-2016	00:55:16	125.7061163	125.0681394	123.5998342	24.22165794	21.45824932	26.26453327	0.456158381	0.514411705	0.510994799

Figure 6.19.a RMS Voltage and Current Values and Power Factor for Three Phase lines.

Date	Time	P1 (Watt)	P2 (Watt)	P3 (Watt)	P(Total) Watt	Q1 (VAR)	Q2 (VAR)	Q3 (VAR)	Q(Total) (VAR)
27-01-2016	00:52:36	2392.805816	2424.867846	2896.415839	7714.089501	4672.470906	4042.723455	4891.59275	13606.78711
27-01-2016	00:52:46	2448.158275	2372.597469	2915.756169	7736.511913	4705.494415	3958.046779	4890.576981	13554.11817
27-01-2016	00:52:56	2445.595462	2406.362101	2868.069328	7720.026891	4714.612188	4010.976239	4831.092446	13556.68087
27-01-2016	00:53:06	2438.443168	2413.034604	2879.307045	7730.784817	4719.179743	4019.690515	4862.969025	13601.83928
27-01-2016	00:53:16	2416.241521	2380.12229	2940.342784	7736.706596	4672.481204	3960.064475	4908.917801	13541.46348
27-01-2016	00:53:26	2397.940691	2409.080044	2863.637225	7670.657959	4683.637282	4028.34221	4851.299603	13563.2791
27-01-2016	00:53:36	2391.924498	2406.450674	2888.347562	7686.722734	4654.484512	3999.74337	4851.835793	13506.06368
27-01-2016	00:53:46	2425.461647	2351.101895	2890.731998	7667.29554	4725.61582	3959.796926	4893.066003	13578.47875
27-01-2016	00:53:56	2407.326057	2347.408157	2905.329912	7660.064127	4653.141218	3919.080977	4867.574615	13439.79681
27-01-2016	00:54:06	2415.895128	2380.97269	2864.278526	7661.146345	4705.375526	3977.697133	4844.157386	13527.23005
27-01-2016	00:54:16	2392.580024	2405.712336	2881.909934	7680.202295	4677.242204	4010.604678	4861.885398	13549.73228
27-01-2016	00:54:26	2385.483086	2399.867327	2876.831191	7662.181605	4673.222287	4003.505318	4858.391414	13535.11902
27-01-2016	00:54:36	2421.541541	2386.227645	2855.854878	7663.624064	4687.04256	3977.957844	4815.76049	13480.76089
27-01-2016	00:54:46	2393.547164	2387.385973	2870.761124	7651.694261	4687.311409	3985.884726	4838.480438	13511.67657
27-01-2016	00:54:56	2429.427494	2334.669795	2915.17067	7679.267959	4735.65381	3932.792807	4898.090178	13566.53679
27-01-2016	00:55:06	2419.6986	2321.439634	2894.752487	7635.890721	4678.834951	3882.779222	4839.245201	13400.85937

Figure 6.19.b Active and Reactive Power for Three phase lines in Excel Sheet

Date	Time	T1 (°C)	T2 (°C)	T3 (°C)	T(House air average) (°C)	T(out) (°C)	Irrad (W/m2)	Pressure (Hg)	Air Flow1 (kg/h)	Air Flow2 (kg/h)	Total Air Flow (kg/h)
27-01-2016	00:52:35	21.94115062	22.4360756	21.26538178	21.88086933	16.43177569	13.23345949	27.20703704	2536.571881	1059.301283	3595.873164
27-01-2016	00:52:45	21.81240924	22.24093823	21.11262672	21.7219914	16.53207945	13.23024084	27.2102557	2536.80033	1059.247665	3596.047995
27-01-2016	00:52:55	21.72845301	22.07947084	20.92730021	21.57840802	16.38362203	13.23489	27.19248874	2537.620058	1059.375327	3596.995386
27-01-2016	00:53:05	21.68829168	21.94258613	20.7219948	21.45095753	16.41830692	13.24490358	27.18330486	2538.664876	1059.219579	3597.884455
27-01-2016	00:53:15	21.59368759	21.83613046	20.6686145	21.36614418	16.3677323	13.23274423	27.15515239	2532.117125	1058.078275	3590.1954
27-01-2016	00:53:25	21.470885	21.6702086	20.44361816	21.19490392	16.26984132	13.23167135	27.13927371	2533.746504	1058.808505	3592.55501
27-01-2016	00:53:35	21.37699415	21.55928831	20.25490731	21.06372992	16.27332399	13.23131372	27.13961703	2531.586317	1058.203384	3589.789701
27-01-2016	00:53:45	21.29243484	21.4454014	20.09215724	20.94333116	16.18657162	13.23596288	27.14811427	2529.842712	1056.919097	3586.76181
27-01-2016	00:53:55	21.27326067	21.411465	20.01902546	20.90125038	16.15914447	13.23310186	27.15390784	2533.471022	1057.953165	3591.424187
27-01-2016	00:54:05	21.15402947	21.43347531	19.82214244	20.80321574	16.22382783	13.22809507	27.15957267	2533.403831	1058.147212	3591.551043
27-01-2016	00:54:15	21.03692482	21.39978583	19.72204727	20.71958598	16.19373562	13.2323866	27.16240508	2530.685959	1056.71739	3587.403349
27-01-2016	00:54:25	20.95645076	21.38812799	19.56589816	20.63682564	16.24231459	13.24025442	27.16540916	2538.765663	1059.370221	3598.135883
27-01-2016	00:54:35	20.90450417	21.26757997	19.4637934	20.54529251	16.30828781	13.23095609	27.18008621	2538.644719	1059.150641	3597.79536
27-01-2016	00:54:45	20.78694515	21.12914948	19.36675653	20.42761705	16.27294248	13.2323866	27.17570884	2537.720845	1059.074043	3596.794888
27-01-2016	00:54:55	20.69126703	20.95691007	19.21991366	20.28936359	16.34994872	13.24061204	27.18004329	2535.352367	1058.504668	3593.857035
27-01-2016	00:55:05	20.62338512	20.83424552	19.09070243	20.18277769	16.40031002	13.22916795	27.1828757	2532.742	1056.977822	3589.719823
27-01-2016	00:55:15	20.54836335	20.84980143	18.94362859	20.11393112	16.27257667	13.23274423	27.18446357	2531.593036	1058.21615	3589.809186

Figure 6.19.c Environmental Parameters in Excel Sheet

CHAPTER 7

COMPARISON DATA MEASUREMENT AND SIMULATION RESULTS

In this chapter, the measurement data and simulation results of each approach mentioned previously will be presented. Simulation results for ON/OFF cycle and VFD systems are validated with measurement data in this chapter. All data sources will be analyzed individually to make a comparison for the results obtained from each systems. In both models, ON/OFF and VFD HVAC approach, two models are analyzed and validated with measurement data, namely, for low heat load day, normal heat load day and introduced heat day. The energy used for both HVAC simulation systems is compared to the actual energy used for two HVAC houses and then the saving energy is also calculated. Validate procedure for both ON/OFF and VFD HVAC systems will be discussed in next sections.

7.1 Validate Simulation Results with Measurement Data for ON/OFF Cycle HVAC System

Simulation results for in-house air temperature and consuming power values on three days, low activity day (5^{th} of March, 2016), normal activity day (9^{th} of April, 2016), and introduce activity (21^{st} of April, 2016) are gotten by Simulink Matlab. The simulation values are built by Simulink Matlab on ON/OFF air conditioning unit. Measurement data are collected by LabVIEW program for house #3305, these data are validated with the simulation values for both in-house air temperature and consuming power. Setting temperature is 24 ^{o}C with fluctuation (+1 ^{o}C & -3 ^{o}C) and the initial house temperature 24.1 ^{o}C. The validation for both in-house air temperature and power used for three days are explained clearly in the following sections.

1. Low activities day (March 5th ,2016) for ON/OFF cycle A/C unit

low activities day validation for in-house air temperature is displayed in figure 7.1. The simulated values (blue color) are fluctuated similarly with the measurement values (black color), where the number of pulses are also equals (40 pulses), average cycle period also is identical, and the time working for simulation and measurement are same time (264 min = 4.4 h). The out-house air temperature performance effects directly on the ON/OFF A/C unit, that it effects on the ON pulse number. The out-house air temperature (red color), which shows in figure 7.1, is still constant 23 ^{o}C from midnight to 7:00 AM and then it is raised dramatically at 7:00 AM from 24 ^{o}C to 36 ^{o}C at 12:30. The temperature is again go down slowly to reach ^{o}C at 7:30 PM. Where the house has only permanent activities (fridge, computer, monitor, Wi-Fi, constant light, and printer) that means not social activities in this day.

In beginning day at midnight, OFF time is almost 30 mins and it reaches to 3:30 PM, which is affected by activities in house from 00:00 AM to 2:30 AM. Where activities begin from 9250 Btu and it goes down to reach 7000 Btu as it is displayed in figure 7.2. From 3:30 AM to 7:00 AM, OFF time increases to 1 h and 20 mins, which is affected only by reducing out temperature and in-house activities. With increase the out-house air temperature from

07:00 AM to 10:00 AM, the OFF time still high and it is reached to 1 h that is affected directly by tree's shadow that is close to east window as we are shown in figure 6.1. From 10:00 AM to 6:00 PM, ON/OFF frequency is increased effecting by increase ambient temperature, so OFF time is reduced and it is reached to 15 mins. ON/OFF frequency again is reduced effecting by reduce ambient temperature to 25 ^{o}C, so OFF time increase slowly and it reaches to 30 mins. The permanent activities in house is totaled and presented in figure 7.2. We show the activities close to 9250 Btu through night from midnight to 3:00 AM and it still 7500 Btu from 3 am to 5:30 PM. The activities increase slowly at 6:00 AM and it reaches to 7750 Btu that is affected by living people in house.

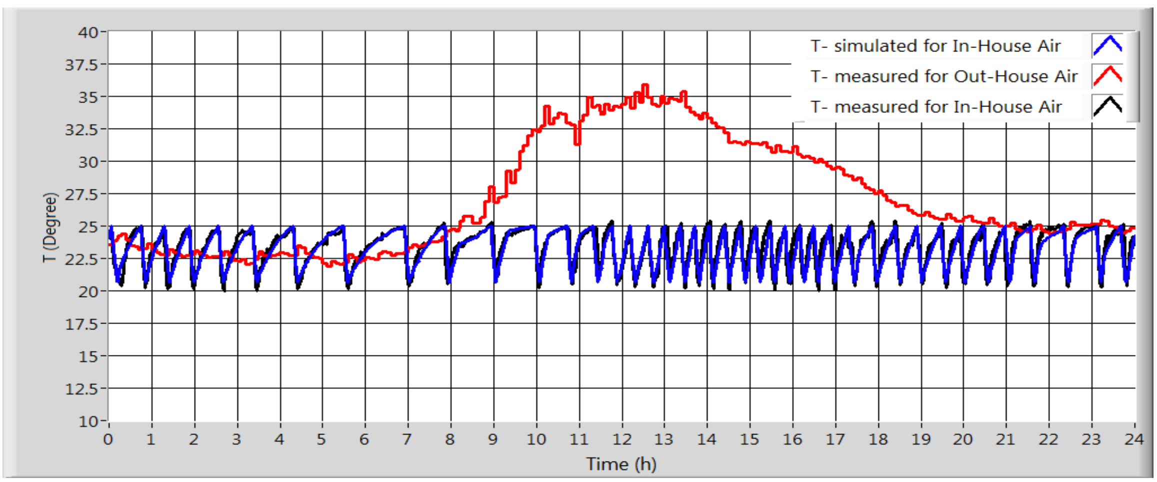


Figure 7.1 Out House Air Measured Temperature and In-House Air Measured and Simulated Temperatures on 5th of March

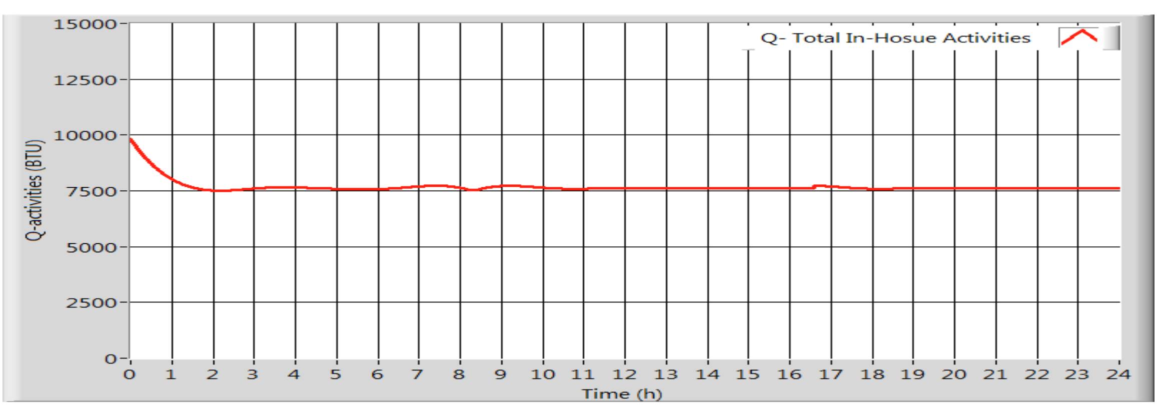


Figure 7.2 In-House Permanent Activities on 5th of March 2016

Power used validation for ON/OFF cycle unit on 5th of March is displayed in figure 7.3. The simulated values (blue color) are similar the measurement values (red color) 4.95 KW, where ON/OFF pulse numbers are also equals (40 pulses) and the time working for simulation and measurement are same time (237 min = 3.95 h). The out-house air temperature (red color) that presented in figure 7.1 it rises at 10:00 am to 32 ^{o}C till it is reached to 36 ^{o}C in midday this causes to increase the temperature on compressor so the condenser of A/C unit starts to increase power used to be ambient compressor appropriate. Where the condenser of A/C unit is connected directly with compressor supply the total power used reached to 5.4 KW. On other ways, when the ambient temperature is reached to 25 ^{o}C the compressor A/C unit temperature is reduced so the condenser power used also reduced, the total power consumption goes down to the schedule power 4.95 KW.

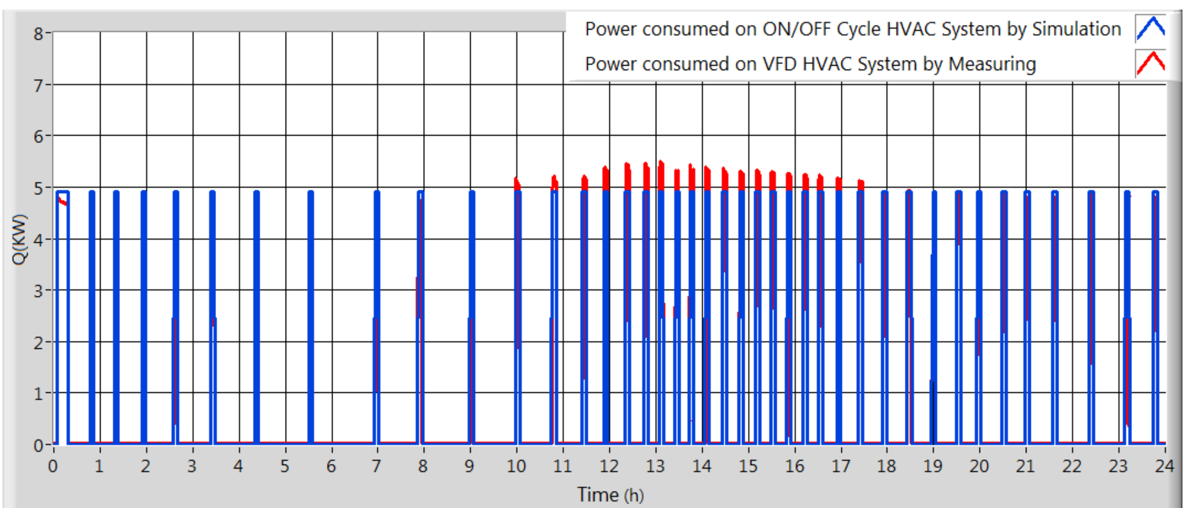


Figure 7.3 Measured and Simulated Consuming Power for ON/OFF cycle A/C Unit on 5th of March

2. Normal activities day (April 9th ,2016) for ON/OFF cycle A/C unit

Normal activities day validation for in-house air temperature is shown in figure 7.4. Similarly, simulated values (blue color) are fluctuated similarly with the measurement values (black color) where the number of pulses are also equals (49 pulses), average cycle period also is identical, and the time working for simulation and measurement are same time (384 min = 6.4 h). The out-house air temperature performance effects directly on the ON/OFF A/C unit, that it effects on the ON pulse numbers. The out-house air temperature (red color), which is displayed in figure 7.4, is still constant 23 ^{o}C from midnight to 6:00 AM and then it is raised dramatically at 6:00 AM from 23 ^{o}C to 42.5 ^{o}C at 12:30. The temperature again is gone down slowly to reach 25 ^{o}C at 7:30 PM. Where the house has permanently activities (fridge, computer, monitor, Wi-Fi, constant light, and printer) and the social activities (cooking breakfast, lunch & dinner, washing machine, open/close door and windows frequently time) that means high activities occurring in this day.

In beginning day at midnight, OFF time is almost 33 mins and it reaches to 2:30 PM which is affected by activities in house from 00:00 AM to 2:30 AM. Where activities begin from 8050 Btu and it goes up to reach 9500 Btu and then it goes down to 6500 Btu as it was shown in figure 7.5 with remain out-house temperatures 23 ^{o}C. From 2:30 AM to 4:00 AM, OFF time increases to 45 mins that is affected by reducing out temperature to 21 oC and reduce in-house activities to 6500 Btu. With increase the out-house air temperature from 05:30 AM to 10:00 AM, the OFF time still high and it is reached to 1 h that is affected directly by tree's shadow that is close to east window as we were shown in figure 6.1. From 10:00 AM to 6:00 PM, ON/OFF frequency is increased effecting by increase ambient temperature that reaches to 42.5 ^{o}C in midday and the social activities (lunch dinner, washing machine, open/close windows and door, , etc.),, so OFF time is reduced and it reaches to 13 mins. ON/OFF frequency again is reduced slowly effecting by reducing ambient temperature to 26 ^{o}C and remain some of social activities (cooking dinner, boiling tea water, , etc.), so OFF time increase slowly and it reaches to 20 mins. The permanent and social activities in house is totaled and presented in figure 7.5. We show starting activities from 8050 Btu and then it goes up to 9500 Btu and then it goes down to 6500 Btu from midnight to 2:30 AM and it increased to 12000 Btu in midday effecting by social activities (cooking lunch, washing machine, open/close windows and door, , etc.). The activities are reduced slowly to 8000 Btu at 4:00 PM and it is increased to 11000 Btu effecting by cooking dinner and boiling tea water.

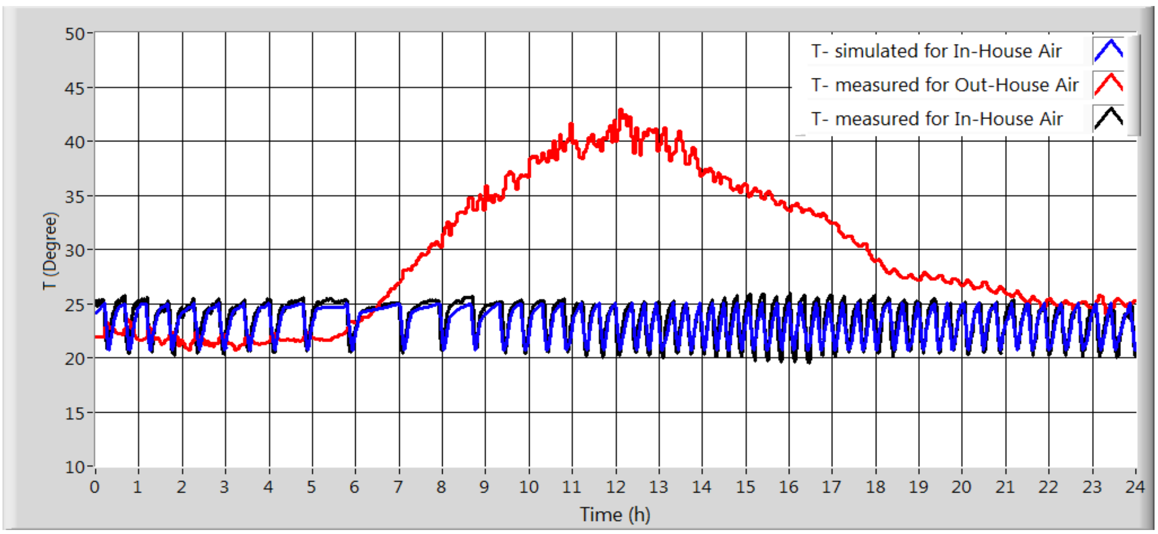


Figure 7.4 Out House Air Measured Temperature and In-House Air Measured and Simulated Temperatures on 9th of April

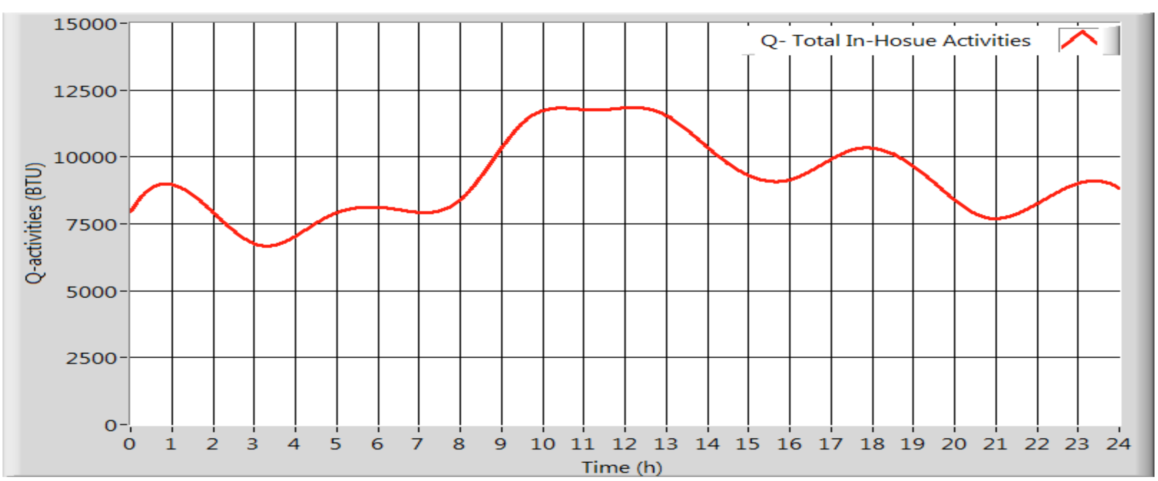


Figure 7.5 In-House Permanent and Social Activities on 9th of April

Power used validation for ON/OFF cycle unit on 9th of April is presented in figure 7.6. The simulated values (blue color) are similar the measurement values (red color) 4.95 KW, where ON/OFF pulse numbers are also equals (45 pulses) and the time working for simulation and measurement are same time (249 min = 4.14 h). The out-house air temperature (red color) that displayed in figure 7.4, it is went up at 10:00 am to 32 ^{o}C till it is reached to 42.5 ^{o}C at 12:30 this causes to increase the temperature on compressor so the condenser of A/C unit starts to increase power used. Where the condenser of A/C unit is connected directly with compressor supply, the total power used is reached to 5.4 KW. On other ways, when the ambient temperature reaches 27.5 ^{o}C the compressor A/C unit temperature is reduced so the condenser power used also reduced, the total power used reaches the schedule power 4.95 KW.

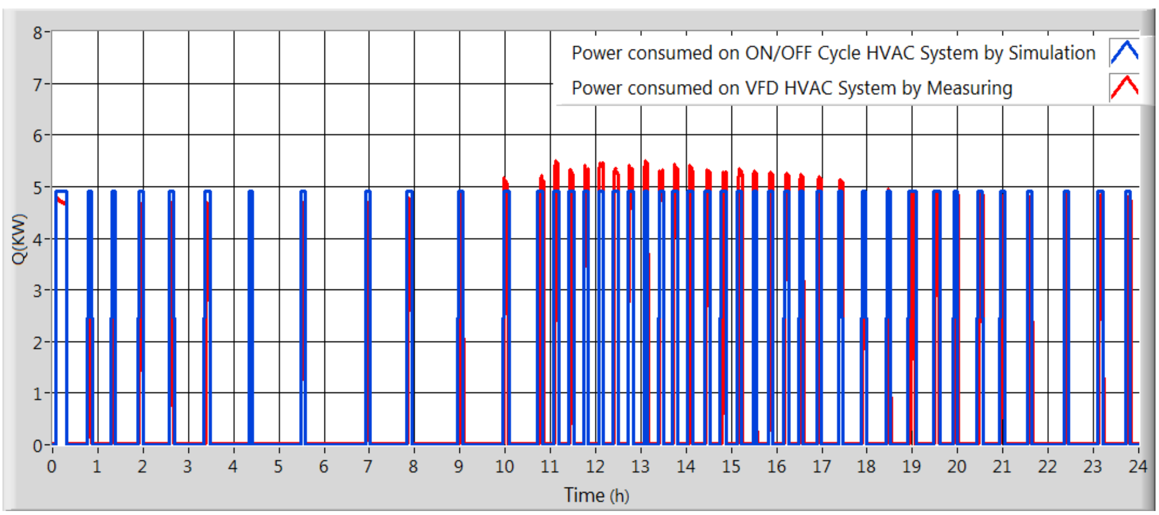


Figure 7.6 Measured and Simulated Consuming Power for ON/OFF cycle A/C Unit on 9th of April 2016

3. Introduce activities day (April 21st ,2016) for ON/OFF cycle A/C unit

Introduce heat activities day validation for in-house air temperature is displayed in figure 7.7. Similarly, simulated values (blue color) are fluctuated similarly with the measurement values (black color) where the number of pulses are also equals (50 pulses), average cycle period also is identical, and the time working for simulation and measurement are same time (348 min = 5.8 h). The out-house air temperature performance effects directly on the ON/OFF A/C unit, that it effects on the ON pulse numbers. The out-house air temperature (red color), which is presented in figure 7.7, is still constant 26 ^{o}C from midnight to 6:00 AM and then it is raised dramatically at 6:00 AM from 23 ^{o}C to 38 ^{o}C at 11:00 AM. The temperature again goes down slowly to reach 27 ^{o}C at midnight. Where the house has permanently activities (fridge, computer, monitor, Wi-Fi, constant light, and printer) and the social activities (cooking breakfast, lunch & dinner, washing machine, open/close door and windows frequently time), we introduce positive and negative activities heat to check our simulator working with measurement data.

In beginning day at midnight, OFF time is almost 33 mins and it is reached to 2:30 PM, which is affected by activities in house from 00:00 AM to 2:45 AM. Where activities begin from 8750 Btu and then it goes down to reach 8000 Btu as it is shown in figure 7.8 with remain out-house temperatures 27 ^{o}C. From 2:45 AM to 4:00 AM, OFF time increases to 50 mins which is affected by small reducing out temperature to 25.5 ^{o}C for 35 mins and reduce in-house activities to 7000 Btu at 7:00 AM. With increase the out-house air temperature from 05:30 AM to 10:00 AM, the OFF time still high and it is reached to 1 h that is affected directly by tree's shadow that is close to east window as we see in figure 6.1. From 10:00 AM to 1:30 PM, ON/OFF frequency is increased effecting by increase ambient temperature that reaches to 38 ^{o}C in midday and the social activities 11000 Btu (lunch dinner, washing machine, open/close windows and door, , etc.),, so OFF time is reduced and it is reached to 13 mins. Negative heat activities are occurred by covering east and west big windows and they are started from 1:30 PM to 3:20 PM as it is displayed in figure 7.8. ON/OFF frequency is reduced through this time and OFF time is reached to 40 mins. positive heat activities are occurred by opening east, west big windows and door and they are started from 3:30 PM to 6:00 PM as it is displayed in figure 7.8. ON/OFF frequency is increased through this time and OFF time is reached to 15 mins. ON/OFF frequency again is reduced slowly effecting by reducing ambient temperature to 27 ^{o}C and remain some of social activities (cooking dinner, boiling tea water, etc.), so OFF time increase slowly and it is reached to 20 mins. The permanent and social activities with introduce heat in house is totaled and presented in figure 7.8. We displayed starting activities from 8750 Btu and then it goes down to 8000 Btu and then it goes up from 7000 Btu at 7:15 AM to 11000 Btu at 1:30 PM. Negative activity loads are added from 1:30 PM to 3:20 PM by covering windows and reduce in-house activities and the heat is reached to 8000 Btu. Positive activity loads are added from 3:22 PM to 7:00 PM by open windows and door and the heat is reached to 10700 Btu. The activities are reduced slowly to 7500 Btu at 7:00 PM and it is increased to 9000 Btu effecting by cooking dinner and boiling tea water.

Power used validation for ON/OFF cycle unit on 9th of April is presented in figure 7.9. The simulated values (blue color) are similar the measurement values (red color) 4.95 KW, where ON/OFF pulse numbers are also equals (50 pulses) and the time working for simulation and measurement are same time (348 min = 5.8 h). The out-house air temperature (red color) which displayed in figure 7.7, it is went up at 10:00 am to 35 ^{o}C till it reaches to 38 ^{o}C at 11:00 this causes to increase the temperature on compressor so the condenser of A/C unit starts to increase power used. Where the condenser of A/C unit is connected directly with compressor supply, the total power used is reached to 5.4 KW. On other ways, when the ambient temperature reaches 28 °C the compressor A/C unit temperature is reduced so the condenser power used also reduced, the total power used reaches the schedule power 4.95 KW.

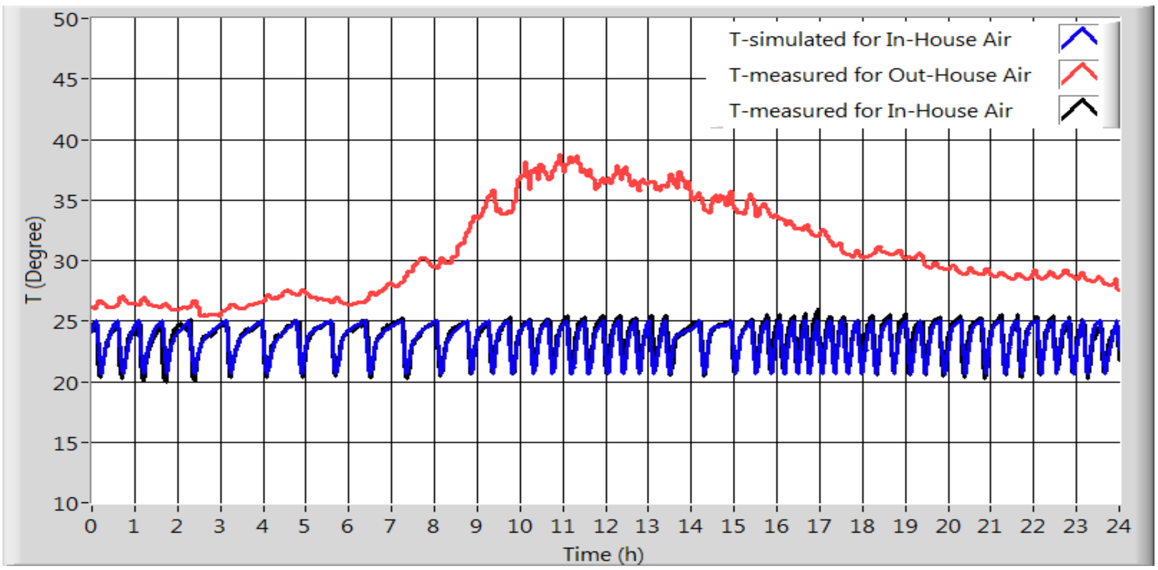


Figure 7.7 Out House Air Measured Temperature and In-House Air Measured and Simulated Temperatures on 21st of April

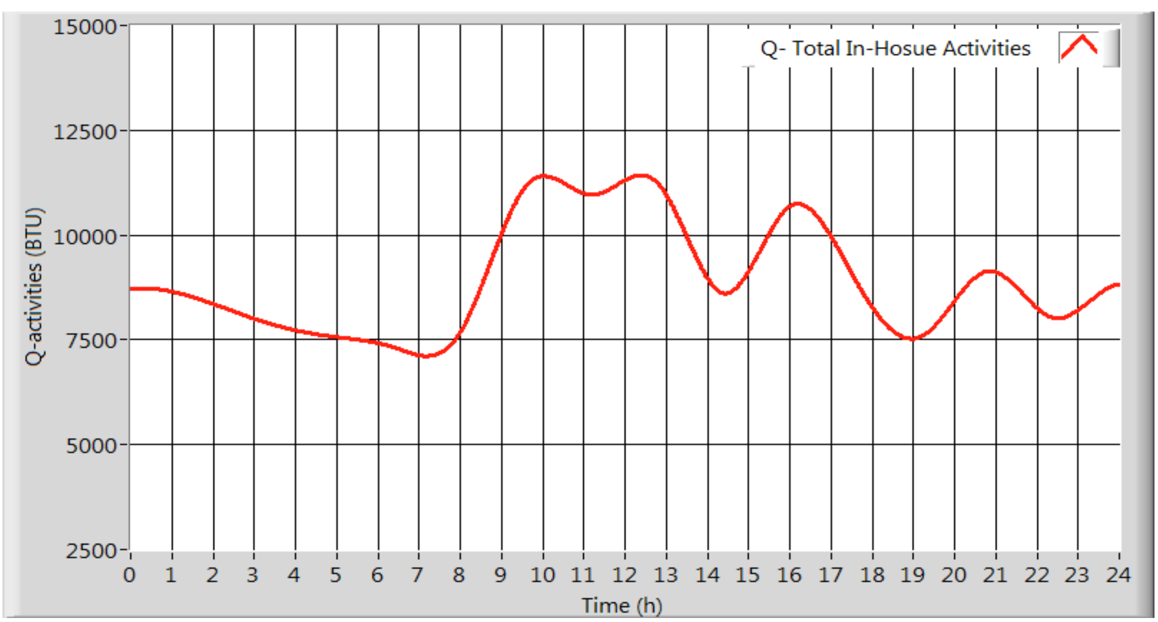


Figure 7.8 In-House Permanent, Social, and Introduce Activities on 21st of April 2016

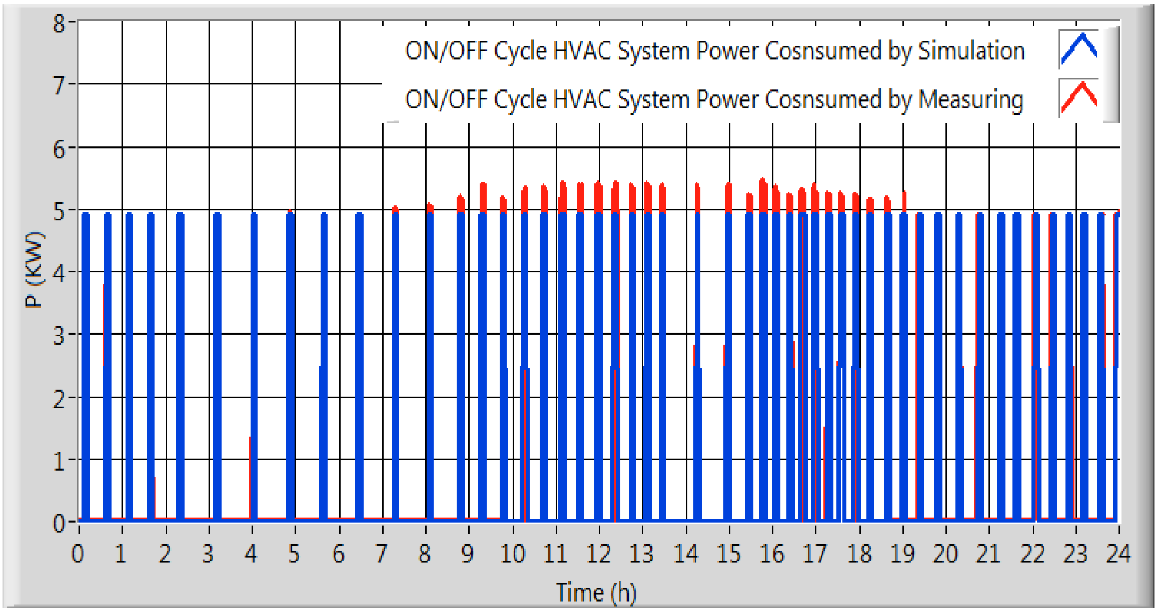


Figure 7.9 Measured and Simulated Consuming Power for ON/OFF cycle A/C Unit on 21st of April 2016

7.2 Validate Simulation Results with Measurement Data for VFD HVAC System

Simulation results for in-house air temperature and consuming power values on three days, low activity day (5th of March, 2016), normal activity day (9th of April, 2016), and introduce activity (21st of April, 2016) are gotten by Simulink Matlab. The simulation values are built by Simulink Matlab on VFD A/C unit for house #3307. Measurement data are collected by LabVIEW program, data are validated with the simulation values for both in-house air temperature and consume power. Setting temperature is 24 °C and the initial house temperature 23.2 °C. The validation for both in-house air temperature and power used for three days are explained clearly in the following sections.

1. Low activities day (March 5th ,2016) for VFD A/C unit

Low activities day validation for in-house air temperature is displayed in figure 7.10. The simulated results (blue color) are similar the measurement values (black color), where the temperature for both values are in same level (24.5 ^{o}C to 23 ^{o}C). The out-air temperature effects directly on the VFD A/C unit performance, as we are displayed in figure 7.11, where the amount of flow rate is increased and decreased to be the simulated and measured temperatures are closely on the setting temperature (24 ^{o}C).

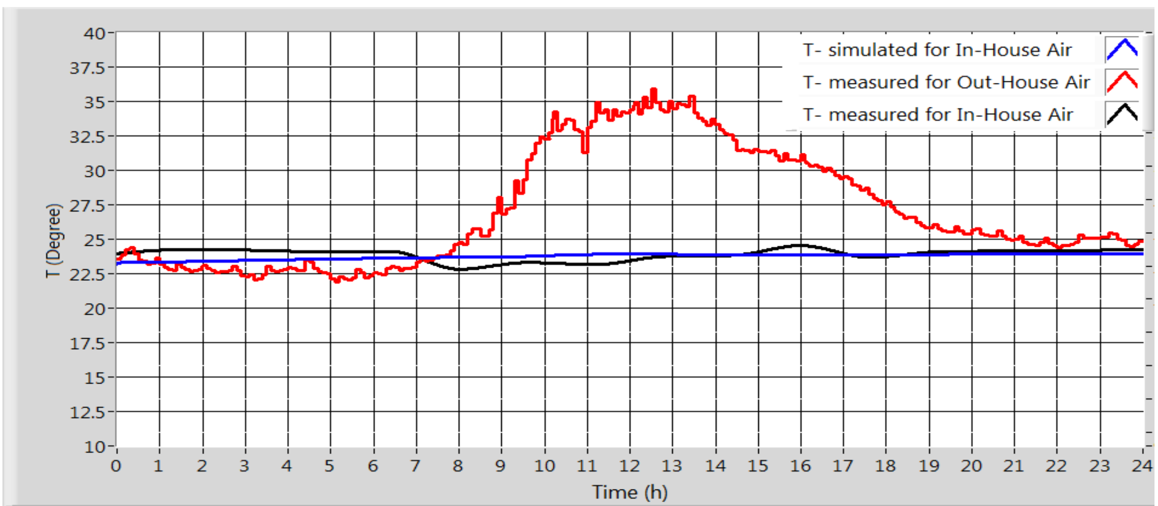


Figure 7.10 Out House Air Measured Temperature and In-House Air Measured and Simulated Temperatures on 5th of March, 2016

Low activities day validation for in-house power used is also displayed in figure 7.11. The simulated results (blue color) are appeared similar the measurement values (red color), where the amount of consuming power is increased and decreased smoothly depending on the activities in-house load and ambient temperature. As we see the power flow in this case only is effected by out-house air temperature, so VFD A/C unit start to rise consuming power at 09:00 am and it is reached maximum value (1.5 KW) in midday (12:00 pm). The power flow is reduced slowly till it is reached to 0.18 KW at 03:00 am and then it is again raised to 0.45 KW and then it is fixed to flow on 0.2 KW till mid-night.

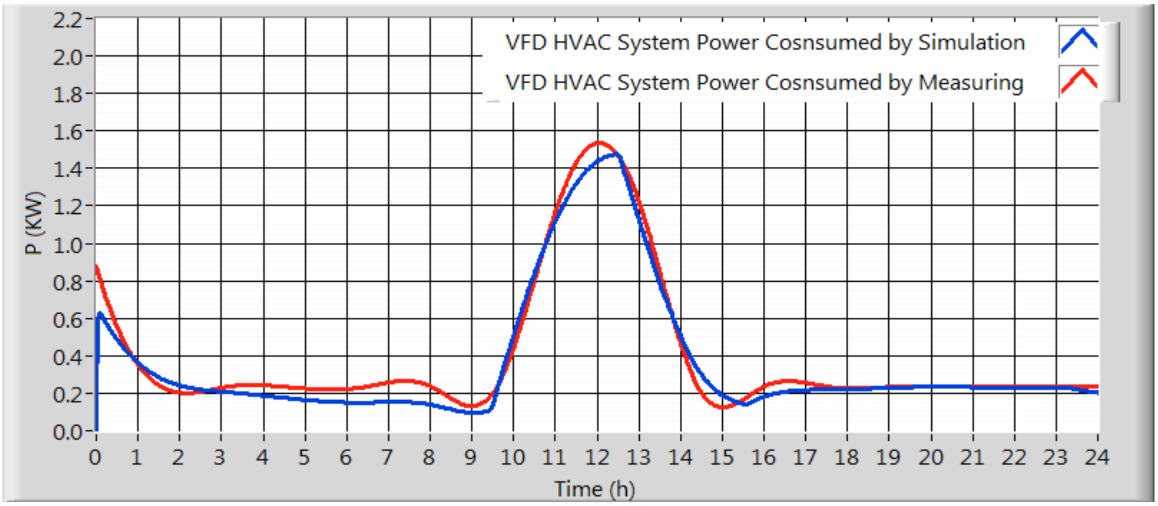


Figure 7.11 Measured and Simulated Consuming Power for VFD A/C Unit on 5th of March, 2016

2. Normal activities day (April 9th ,2016) for VFD A/C unit

Similarly, normal activities day validation for in-house air temperature is displayed in figure 7.12. The simulated results (blue color) are similar the measurement values (black color), where the temperature for both values are in same level (24.5 °C to 23 °C). The out-air temperature and normal activities (permanent and social heat load) effect directly on the VFD A/C unit performance, as we are displayed in figure 7.13, where the amount of flow rate is increased and decreased to be the simulated and measured temperatures are closely the setting temperature (24 °C).

Normal activities day validation for in-house power used is also displayed in figure 7.13. The simulated results (blue color) are appeared similar the measurement values (red color), where the amount of consuming power is increased and decreased smoothly depending on in-house activities (permanent and social activities) and ambient temperature. As we see the power flow is started to rise at 05:30 AM and the consuming power is reach maximum values (1.7KW) at 10:00 AM 12:00 PM effecting by in-house activities (cooking breakfast/lunch, washing machine, open/close windows and door, ...etc.), and ambient temperature. The power flow reduces slowly till reach 0.9 KW at 03:00 PM and it is again raised to 1.3 KW effecting by in-house activities (cooking denier, washing machine, open/close door, boiling tea water, ...etc.), then it goes down to 0.4 KW till 09:00 pm and finally it goes up to 0.9 KW at midnight.

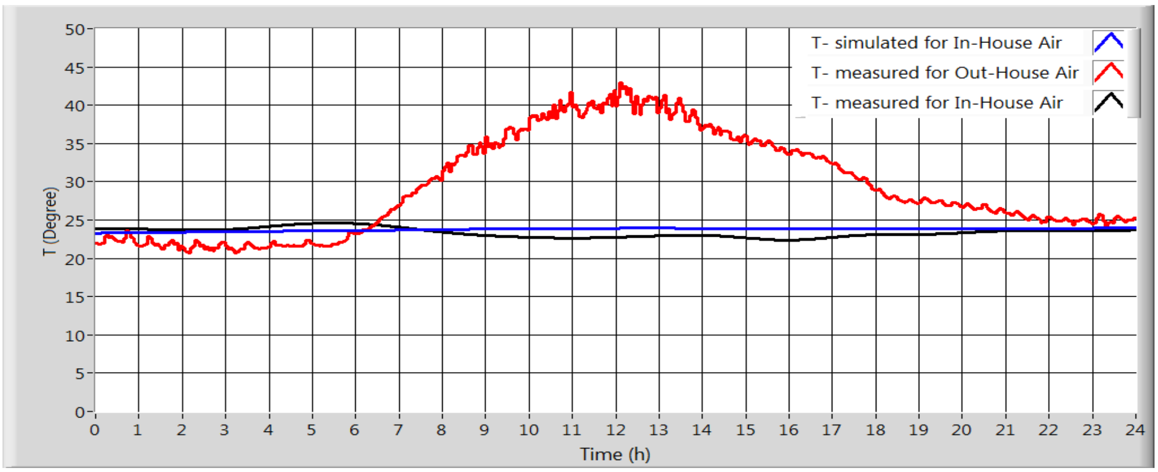


Figure 7.12 Out House Air Measured Temperature and In-House Air Measured and Simulated Temperatures on 9th of April, 2016

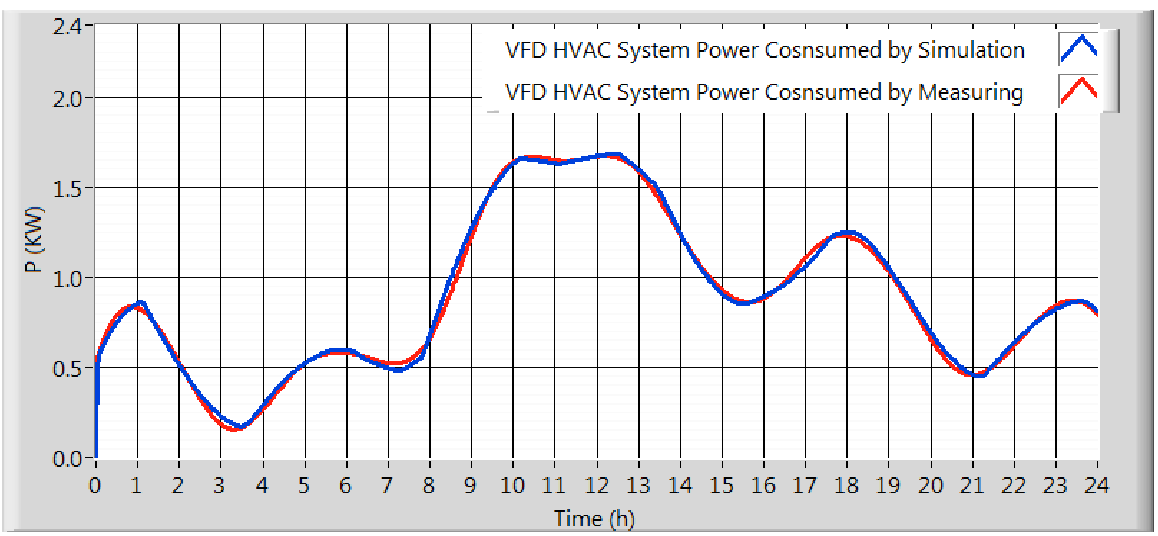


Figure 7.13 Measured and Simulated Consuming Power for VFD A/C Unit on 9th of April, 2016

3. Introduce activities day (April 21st ,2016) for VFD A/C unit

Similarly, introduce heat activities validation day for in-house air temperature is displayed in figure 7.14. The simulated results (blue color) are similar the measurement values (black color), where the temperature for both values are in same level (24.5 ^{o}C to 23 ^{o}C). The out-air temperature and introduce heat activities (permanent, social, and positive/negative heat load) effect directly on the VFD A/C unit performance, as we are displayed in figure 7.15, where the amount of flow rate is increased and decreased to be the simulated and measured temperatures are closely the setting temperature (24 ^{o}C).

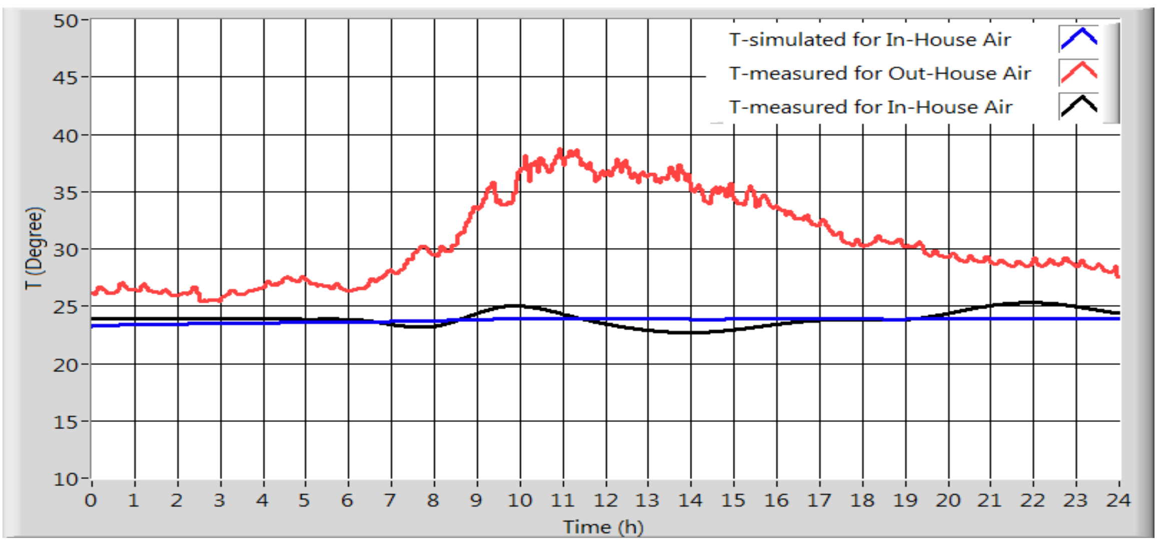


Figure 7.14 Out House Air Measured Temperature and In-House Air Measured and Simulated Temperatures on 21st of April

Introduce heat activities validation day for in-house power used is also displayed in figure 7.15. The simulated results (blue color) are appeared similar the measurement values (red color), where the amount of consuming power is increased and decreased smoothly depending on in-house activities (permanent, social, and positive/negative heat activities) and ambient temperature. As we see the power flow is started to rise at 07:30 and the consuming power is reached maximum values (1.6 KW) at 10:00 AM 12:00 PM effected by in-house activities (cooking breakfast/lunch, washing machine, open/close windows and door, ...etc.), and ambient temperature. The power flow is reduced suddenly affected by negative heat load (covering windows) at 1:30 PM and it is reached to 0.7 KW and it is again raised to 1.4 KW effected by positive heat load (open windows and door). The power flow is reduced for second time by reducing the ambient air temperature ant it is reached to 0.4 KW. The power flow is increased again to reach 0.9 KW affected by in-house activities (cooking denier, washing machine, open/close door, boiling tea water, ...etc.) at 9:00 PM, then it goes down to 0.5 KW till 10:30 pm and finally it goes up to 0.8 KW at midnight.

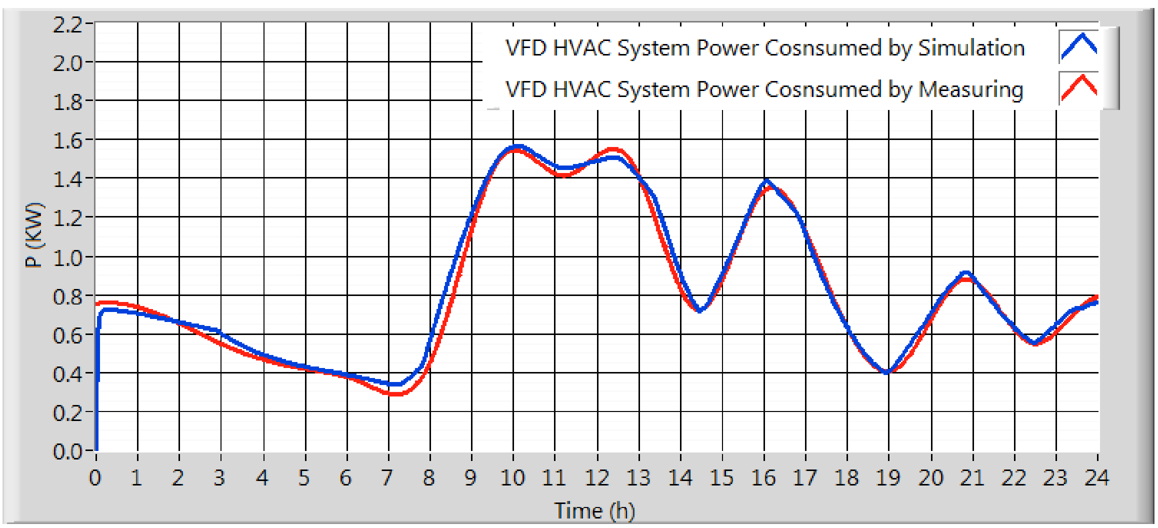


Figure 7.15 Measured and Simulated Consuming Power for VFD HVAC Unit on 21st of April, 2016

7.3 Energy Analysis for Both ON/OFF cycle and VFD HVAC Systems

The energy used for ON/OFF cycle A/C and VFD A/C units is calculated by integrating the area under power consumption curve (KW), which are presented in figures 7.3 & 7.11

for low activities day (March 5th, 2016), figures 7.6 & 7.13 for normal activities day (April 9th, 2016) and figures 7.9 & 7.15 for introduce heat activities day (April 21st, 2016) for both simulation results and measurement data.

1. Low activities day (March 5th ,2016)

For low activity day on 5th of March, energy consumption for measurement data and simulation results that built in ON/OFF Cycle HVAC system, was explained in Table 7.1. The energy used were displayed for measurement and simulation values. The values were similar with small difference reaches to 4.44% in maximum, where it was 21.5 KWh on simulation results and 22.5 KWh on measurement data at end of day.

Similarly, the energy consumption for measurement data and simulation results that built on VFD HVAC system, explained in Table 7.1. The energy used was shown for measurement and simulation values. The values were similar with small difference reaches to 3.6% in maximum, where it was 9.3 KWh on simulation results and 9.8 KWh on measurement data at end of day.

The energy used for both ON/OFF cycle and VFD HVAC systems was calculated by integrating the area under power consumption curve (KW) and it was explained in Table 7.1. The result for integration power area under curve gave 21.5 KWh/day and 9.8 KWh/day for ON/OFF cycle and VFD HVAC systems respectively. Saving energy occurred continuously from starting day until mid-day. At noon, when the ambient temperature is reached high level 36 ^{o}C, so the saving energy reduced that means working VFD HVAC unit closes to rated values value to keep in-house air temperature closely to setting temperature (24 ^{o}C). The total saving energy approximately reached to 56.4% at end of day.

2. Normal activities day (April 9th ,2016)

For normal activity day on 9th of April, the energy consumption for measurement data and simulation results that built in ON/OFF Cycle HVAC system, was explained in Table 7.1. The energy used was displayed for measurement and simulation values. The values were similar with small difference reaches to 1.59% in maximum, where it was 31 KWh on simulation results and 31.5 KWh on measurement data at end of day.

Similarly, the energy consumption for measurement data and simulation results that built on VFD HVAC system was explained in Table 7.1. The energy used was presented for measurement and simulation values. They were similar with small difference reached 0.5% in maximum, where it was 22.4 KWh on simulation results and 22.5 KWh on measurement data at end of day.

The energy used for both ON/OFF cycle and VFD HVAC systems was calculated by integrating the area under power consumption curve (KW) and they were explained in Table 7.1. The Table was displayed results of integration power area that gave 31.5 KWh/day and 22.5 KWh/day for ON/OFF cycle and VFD HVAC systems respectively. The saving of energy used on VFD unit occurred continuously from starting work until mid-day. At noon, when the normal activities load and ambient temperature were reached high level, so the saving of energy reduced that means VFD HVAC unit closes to rated value, to keep in-house air temperature closely to setting temperature (24 ^{o}C). The total saving energy approximately was reached to 28.57% at end of day.

3. Introduce heat activities day (April 21st ,2016)

For introduce heat activity day on 21st of April, the energy consumption for measurement data and simulation results that built in ON/OFF Cycle HVAC system, was explained in Table 7.1. The energy used was displayed for measurement and simulation values. The values were similar with small difference reaches to 3.45% in maximum, where it was 28 KWh on simulation results and 29 KWh on measurement data at end of day.

Similarly, the energy consumption for measurement data and simulation results that built on VFD HVAC system was explained in Table 7.1. The energy used was presented for measurement and simulation values. They were similar with small difference reached 3.17% in maximum, where it was 19.85 KWh on simulation results and 20.5 KWh on measurement data at end of day.

The energy used for both ON/OFF cycle and VFD HVAC systems was calculated by integrating the area under power consumption curve (KW) and they were explained in Table 7.1. The Table was displayed results of integration power area that gave 29 KWh/day and 20.5 KWh/day for ON/OFF cycle and VFD HVAC systems respectively. The saving of energy used on VFD unit occurred continuously from starting work until mid-day. When the introduce heat activities (positive heat load) and ambient temperature were reached to high level, so the saving of energy reduced that means VFD HVAC unit close to rated value to keep in-house air temperature closely to setting temperature (24 ^{o}C). The total saving energy approximately was reached to 29.31% at end of day.

Table 7.1 Energy Analysis for ON/OFF cycle and VFD HVAC Systems on Three days

	Simulated Results				Measurement Data		
	ON/OFF Cycle Unit (KWh)	VFD Unit (KWh)	Saving %		ON/OFF Cycle Unit (KWh)	VFD Unit (KWh)	Saving %
Low activities day (March 5th ,2016)	21.5	9.3	56.7		22.5	9.8	56.4
Normal activities day (April 9th ,2016)	31	22.4	27.74		31.5	22.5	28.57
Introduce heat activities day (April 21st ,2016)	28	19.85	29.29		29	20.5	29.31

The summary of measuring energy used for two months (March and April 2016) that validated with simulation results was explained in Table 7.2. The Comparison energy used for ON/OFF cycle and VFD HVAC units and saving energy presented in table.

Table 7.2 Comparison Consumed Energy for ON/OFF Cycle and VFD HAC Systems in Two Months, 2016

	Simulated Results				Measurement Data		
	ON/OFF Cycle Unit (KWh)	VFD Unit (KWh)	Saving %		ON/OFF Cycle Unit (KWh)	VFD Unit (KWh)	Saving %
March	532.21	292.408	45.24		554.9	282.1	47.32
April	555	331.2	40.32		573	340.5	40.58

CHAPTER 8

CONCLUSIONS AND FUTURE RECOMMENDATION

1.8 Conclusions

In this work, a thermal house-heating model has been developed for a residential air conditioning load. Complete system model is obtained by combining the developed mathematical house heating model with the cooling source model of ON/OFF cycle and VFD air conditioning systems. Model upgrade is achieved by introducing a second order thermal model of house. Upgraded thermal model is then integrated with the developed cooling source models of air conditioning systems. The complete system model is then simulated using Simscape Physical Components developed using MATLAB/SIMULINK tools. The simulation models were tested during highest ambient temperature on 2nd of June 2015 and three days (21st, 22nd, & 23rd) in September 2015. The energy consumed by ON/OFF cycle and VFD air conditioning systems has been recorded. It has been noticed that the energy saving achieved through VFD system has reached to 27% and 24.7% respectively. The energy consumed was examined for several months. The saving energy reached to 27% and 45% during the period from May 2015 to April 2016. It has been noticed that the simulation system performance is affected by the outdoor temperature and the indoor activities during the day. Therefore, saving energy with VFD reached to 45% in medium ambient temperature and furniture activities.

Experimental set-up was built to monitor the various environmental parameters (such as indoor/outdoor temperatures, airflow, pressure, and irradiation) and calculate the energy consumption in two similar houses for the two installed technologies (ON/OFF cycle and VFD system). LabVIEW data acquisition and monitoring program has been developed. The integrated system for thermal house model and electrical model (ON/OFF cycle and VFD model) was validated for real time measurements under different environmental conditions. Experimental measurements on the three days with low, normal, and introduce heat load on March 5, April 9, and April 21, 2016 were used to validate the simulation results. It has been observed that the simulation results matched significantly with the experimental data measurement with a difference of about 3%.

8.2 Future Recommendation

It is a significant step in KSA energy saving campaign to apply the frequency conversion technology into the central air-conditioning system. Statistics show that KSA's central air-conditioning systems have not had any energy saving function to date, which indicates a huge market for the VFD manufacturers.

- The thermal house model can be further upgraded by taking into consideration the accurate furniture activities and ambient temperature.
- An expression relating the cooling gain ($\dot{M_{HVAC}}$) and the coil temperature $T_{\mathrm{A/C}}$ with the frequency of compressor motor and blower motor could be investigated.
- The developed electrical model can be modified by using intelligent techniques such as neural networks/fuzzy logic and pulse width modulation methods.

References

[1] R. Al-Awaal, "ACs use 70% of electricity consumption in Kingdom," *Saudi Gaz.*, 2013.

[2] "Design Guidelines for Buildings in Saudi Arabia Considering Energy Conservation Requirements," no. February, 2016.

[3] V. F. D. Specifying and H. N. American, "VFD , motor strategies for energy efficiency," pp. 1–5, 2014.

[4] D. Ryder-cook, "Thermal Modelling of Buildings," *U-Value*, pp. 1–23, 2009.

[5] D. A. Coley and J. M. Penman, "Simplified thermal response modelling in building energy management. Paper III: Demonstration of a working controller," *Build. Environ.*, vol. 31, no. 2, pp. 93–97, 1996.

[6] T. Salsbury and R. Diamond, "Performance validation and energy analysis of HVAC systems using simulation," pp. 5–17, 2000.

[7] C. Teodosiu, I. Colda, C. Lungu, and A. Damian, "Simulation of HVAC Systems Energy Consumption," in *2006 First International Symposium on Environment Identities and Mediterranean Area*, 2006, pp. 139–143.

[8] M. Muratori, V. Marano, R. Sioshansi, and G. Rizzoni, "Energy consumption of residential HVAC systems: A simple physically-based model," in *IEEE Power and Energy Society General Meeting*, 2012, pp. 1–8.

[9] S. Karmacharya, G. Putrus, C. Underwood, and K. Mahkamov, "Thermal modelling of the building and its HVAC system using Matlab/Simulink," *2nd Int. Symp. Environ. Friendly Energies Appl. EFEA 2012*, pp. 202–206, 2012.

[10] Y. Wen and W. Burke, "Real-time Dynamic House Thermal Model Identification for Predicting HVAC Energy Consumption," in *IEEE Green Technologies Conference*, 2013, pp. 367–372.

[11] W. Zhang, J. Lian, C.-Y. Chang, and K. Kalsi, "Aggregated Modeling and Control of Air Conditioning Loads for Demand Response," *IEEE Trans. Power Syst.*, vol. 28, no. 4, pp. 4655–4664, 2013.

[12] M. R. Kulkarni and F. Hong, “Energy optimal control of a residential space-conditioning system based on sensible heat transfer modeling,” *Build. Environ.*, vol. 39, no. 1, pp. 31–38, 2004.

[13] E. Elsarrag and Y. Alhorr, “Modelling the thermal energy demand of a Passive-House in the Gulf Region: The impact of thermal insulation,” *Int. J. Sustain. Built Environ.*, vol. 1, no. 1, pp. 1–15, 2012.

[14] “ASHRAE Journal Article Index 2010 _ ashrae.” .

[15] K. Ohyama and T. Kondo, “Energy-Saving Technologies for Inverter Air Conditioners,” *IEEJ Trans. Electr. Electron. Eng.*, vol. 3, pp. 183–189, 2008.

[16] J. a. Rooks and A. K. Wallace, “Energy efficiency of VSDs,” *IEEE Ind. Appl. Mag.*, vol. 10, pp. 57–61, 2004.

[17] X. Yu, M. R. Starke, L. M. Tolbert, and B. Ozpineci, “Fuel cell power conditioning for electric power applications : a summary,” *IET Electr. Power Appl.*, vol. 1, pp. 643–656, 2007.

[18] P. E. Systems, “Digital Control Strategy for Efficiency Optimization of a BLDC Motor Driver with VOPFC Chia-Hao Wu Ying-Yu Tzou,” pp. 2528–2534, 2009.

[19] Enemuoh F. O., “Modelling, Simulation and Performance Analysis of A Variable \nFrequency Drive in Speed Control Of Induction Motor,” *Int. J. Eng. Invent.*, vol. 3, no. 5, pp. 36–41, 2013.

[20] J. Rajaraman and K. Saraswathi, “A Labview Based Monitoring and Controlling,” pp. 12679–12684, 2014.

[21] L. Abraham, “Temperature Sensors,” no. December, pp. 277–281, 2014.

[22] G. Shaofeng, M. Jianlin, and W. Xiaodong, “2013 Fourth International Conference on Digital Manufacturing & Automation,” no. 2, pp. 2–5, 2013.

[23] X. Jiang, L. Zhang, and H. Xue, “Designing a Temperature Measurement and Control System for Constant Temperature Reciprocator Platelet Preservation Box Based on LabVIEW,” pp. 48–51, 2008.

[24] H. Xiang, K. Wang, and Z. Li, “Monitored Control System of Temperature / humidity for Ammunition Storehouse Based on LabVIEW,” pp. 172–175, 2011.

[25] V. Aiswarya, “Wind Turbine Instrumentation System using LabVIEW,” pp. 218–222, 2013.

[26] J. Li, L. Xu, and H. Li, “The Application of Automatic Controlling and Measuring System Based on LabVIEW in Thermal Conductivity of Poor Conductor Experiment,” pp. 6082–6084, 2011.

[27] W. Shenghui and C. Yong, “Design of Power Quality Monitoring System based on LabVIEW,” pp. 1026–1029, 2012.

[28] The Engineering Toolbox, “Heat, Work and Energy.” [Online]. Available: http://www.engineeringtoolbox.com/heat-work-energy-d_292.html.

[29] Q. Mechanics, “Types Of Heat Transfer,” *Energy*, 1979. [Online]. Available: http://physics.bu.edu/~duffy/py105/Heattransfer.html.

[30] O. F. Metallic, “Thermal resistance,” 1964. [Online]. Available: https://neutrium.net/tag/thermal-resistance/.

[31] T. Notes, “Combined Conduction and,” *Notes*. .

[32] “HVAC in Construction from Construction Knowledge.” [Online]. Available: http://www.constructionknowledge.net/mechanical/mechanical_hvac.php.

[33] “The Magic of Cold, Part 1 - How Your Air Conditioner Works.” [Online]. Available: http://www.energyvanguard.com/blog-building-science-HERS-BPI/bid/40016/The-Magic-of-Cold-Part-1-How-Your-Air-Conditioner-Works.

[34] “Cooling Loads - Latent and Sensible Heat.” [Online]. Available: http://www.engineeringtoolbox.com/latent-sensible-cooling-load-d_245.html.

[35] “Cooling and Heating Equations.” [Online]. Available: http://www.engineeringtoolbox.com/cooling-heating-equations-d_747.html.

[36] “Calculating Indoor Temperature and Humidity Loads.” [Online]. Available: http://www.engineeringtoolbox.com/indoor-temperature-humidity-d_114.html.

[37] T. Al-Shemmeri, “Building’s Heat Gains,” 2011. [Online]. Available: http://www.wiley.com/legacy/wileychi/al_shemmeri/supp/powerpoints/chapter_5.pdf.

[38] “Basic operation VFD.” .

[39] C. C. Bidwell, “Thermal conductivity of metals,” *Physical Review*, vol. 58, no. 6. pp. 561–564, 1940.

[40] “Specific Heat of some common Substances,” *The Engineering Toolbox*. 2015.

[41] N. R. Canada, “Air Conditioning Your Home,” 1996.

[42] K. Bangmod and K. Thoong-kru, “BLDC COMPRESSOR DRIVER MANUAL (Type A).”

[43] A. Title, “Package BLDC Zamil.” Available: http://www.apyeng.com/manual/BLDC DRIVER MANUAL_Type A_E15_2.pdf.

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- "Modeling and Simulation ON/OFF Cycle and VFD for Air Conditioning System Using Physical Thermal Components in MATLAB/SIMULINK", (under preparation).

- "Modeling, Simulation and Energy Performance OF VFD HVAC System Compared to ON/OFF Cycle HVAC System", (under preparation).